BUTTON Simulations for the Development of WbLS

IOP Joint APP, HEPP and NP Annual Conference: 12th April 2024

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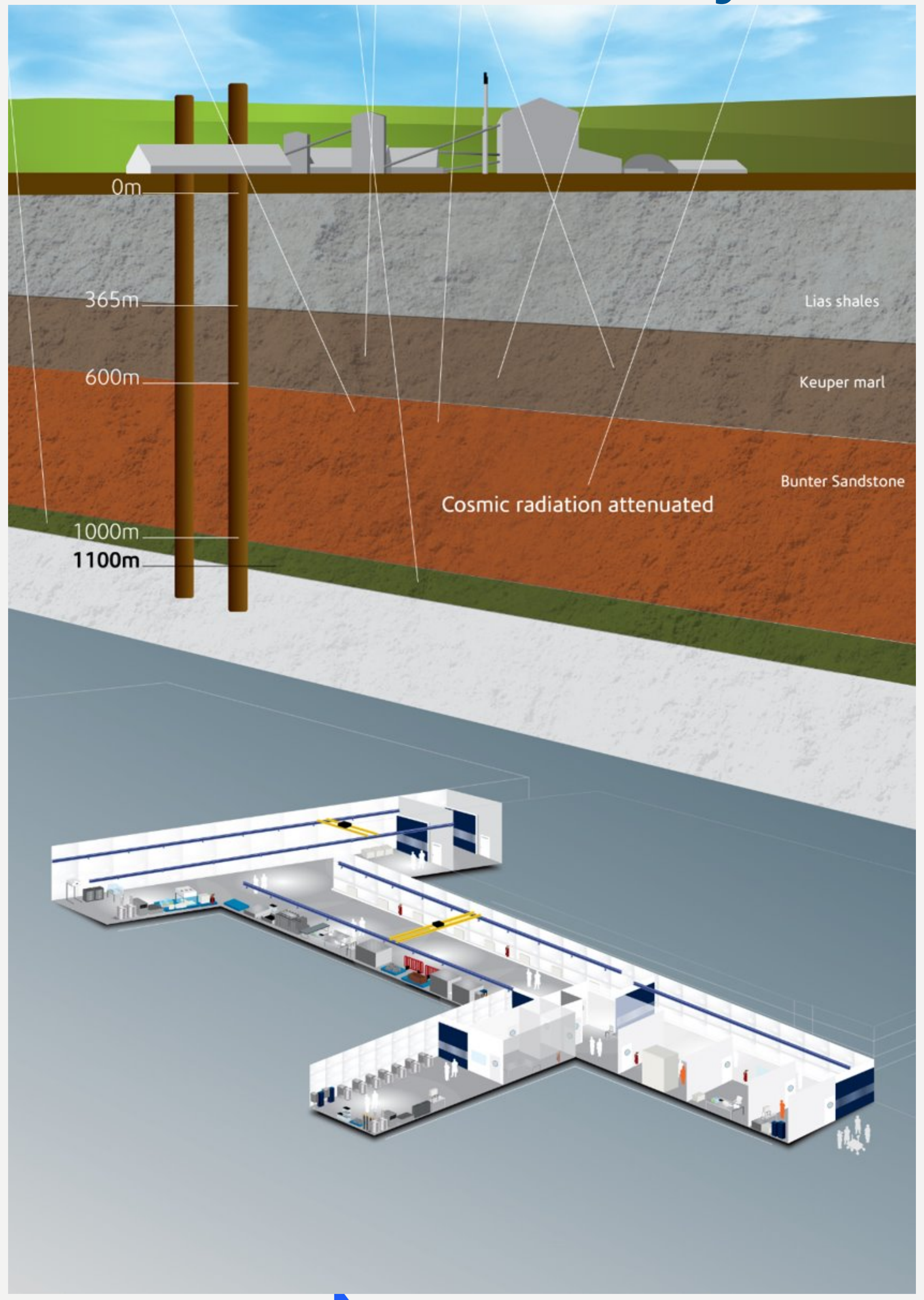
BUTTON a UK/U.S Collaboration

~50 members across 15 institutions in the UK and U.S

ICL Boulby Mine



AWE
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THE UNIVERSITY OF WARWICK
Lawrence Livermore National Laboratory
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Penn
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Pacific Northwest NATIONAL LABORATORY
THE UNIVERSITY of EDINBURGH
University of Glasgow
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Brookhaven National Laboratory
UKRI
Science and Technology Facilities Council
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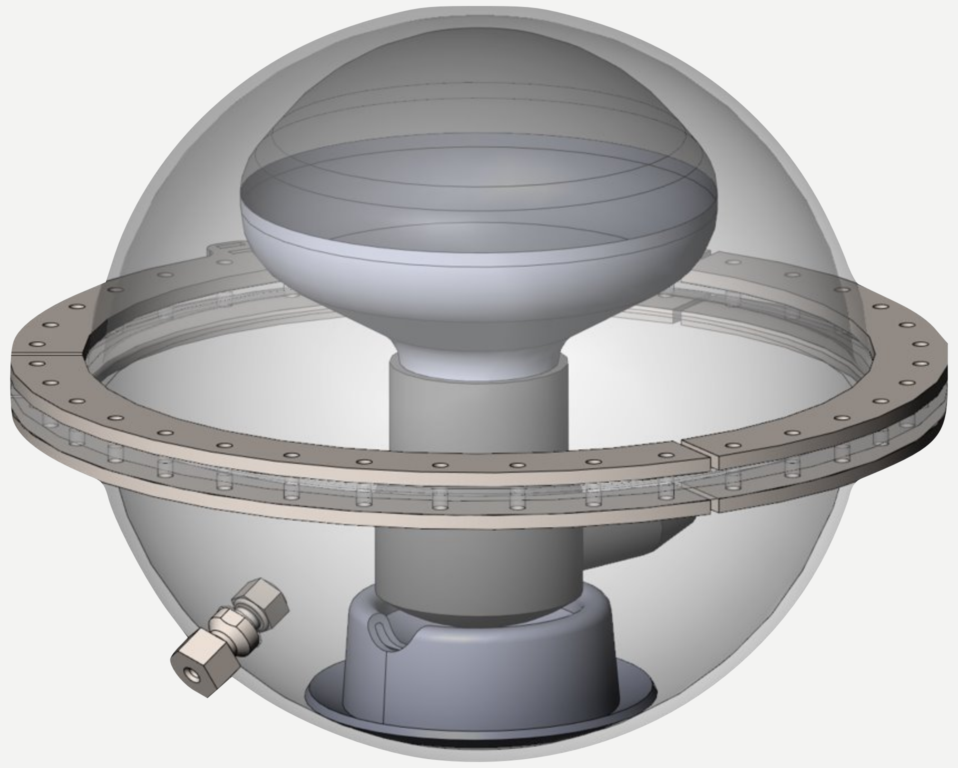
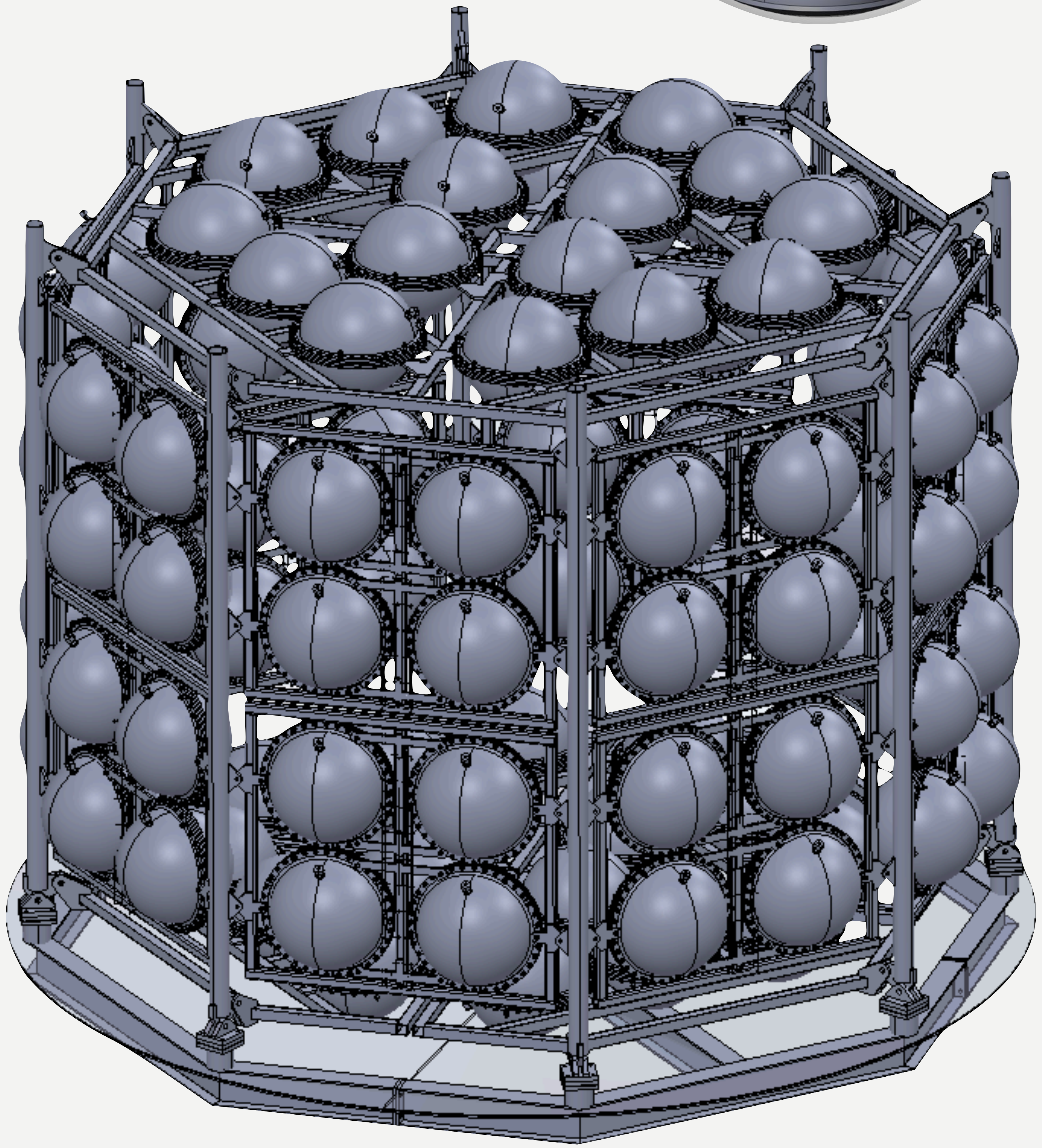
Funded in the UK by STFC from the UKRI Fund for International Collaboration and the MoD,
and in the U.S. by NNSA (National Nuclear Security Administration).

BUTTON

Boulby Underground TesTbed (for) Observing Neutrinos





- Develop technologies for low energy neutrinos observations (MeV)
- 30 tonne (r=1.8 m, h=2.7 m) water-Gd/WbLS-Gd tank
    - Gadolinium improves detection of neutrons
- 96 10” Encapsulated Hamamatsu PMTs
    - Encapsulation protects PMTs from different fill materials
- Potential for novel photosensor deployment
- First underground deployment of WbLS
- Testing the scaling up of the technology

[1] https://arxiv.org/abs/1606.07538

Neutrino Detectors

Low background and low energy detection

- Two classes for low energy (0.1-10 MeV) neutrino detectors

Cherenkov detectors (water)

Advantages

- Great position and direction reconstruction
- Can reconstruct energy of event

Disadvantages

- Limited by Cherenkov threshold 0.8 MeV electron events (total = 4 MeV [1] (SK solar limit with background))
- Poor energy resolution at low energy due to low light yield

Liquid Scintillator

Advantages

- Sensitive to lower energy events (more light per MeV)
- Improved energy resolution (better discrimination from background)

Disadvantages

- Expensive to buy in large quantities
- More challenging to handle 🔥

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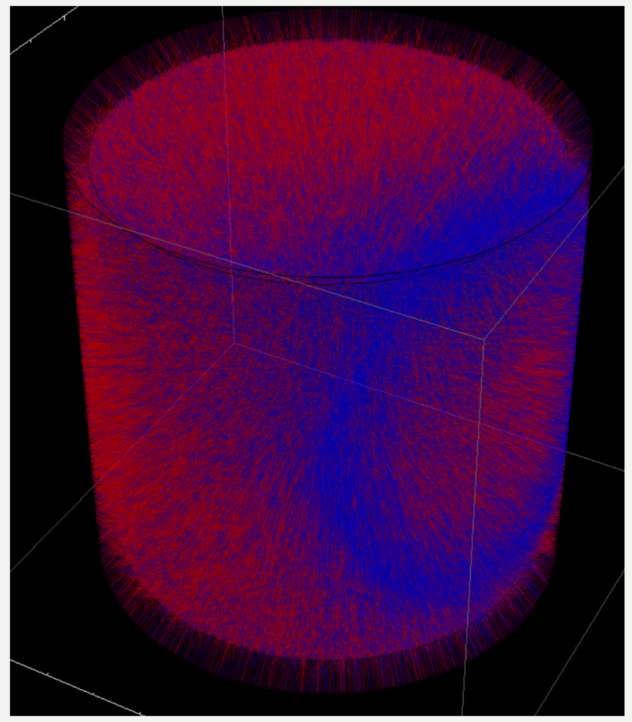
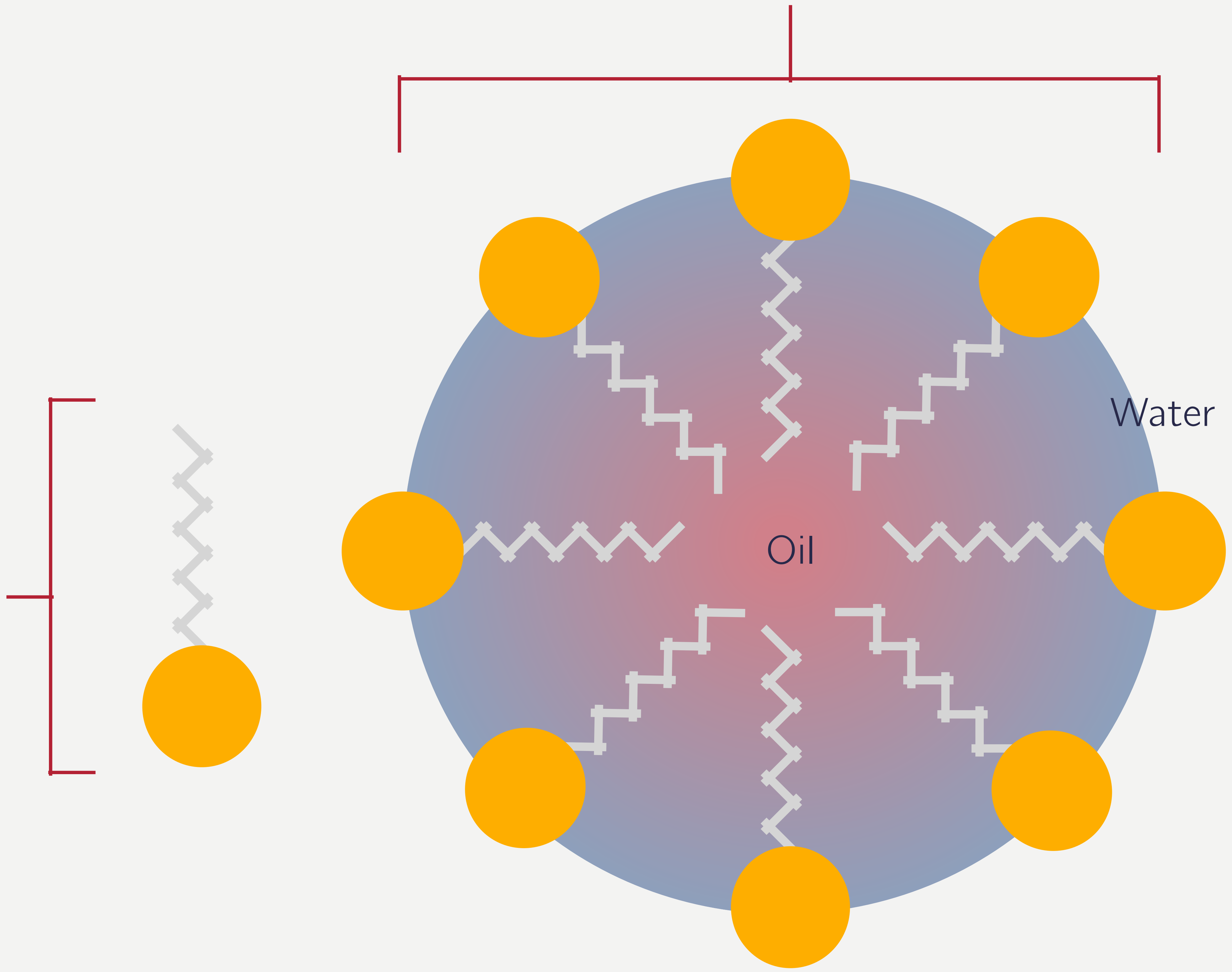
Water-based Liquid Scintillator

A Cherenkov scintillator hybrid

B. Land (Berkeley)



- Why not mix water and scintillator?
- 1% scintillator gives ~100 optical photons/MeV [2]
- Keeps the particle identification and position for high energy events
- Lower detection threshold
- Proposed studies from reactor monitoring, neutrinoless double beta decay, solar neutrinos, diffuse supernova backgrounds .. (THEIA)
- Dark matter vetos (DarkSPHERE, XLZD)



[2] arXiv:1409.5864

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BUTTON under Construction

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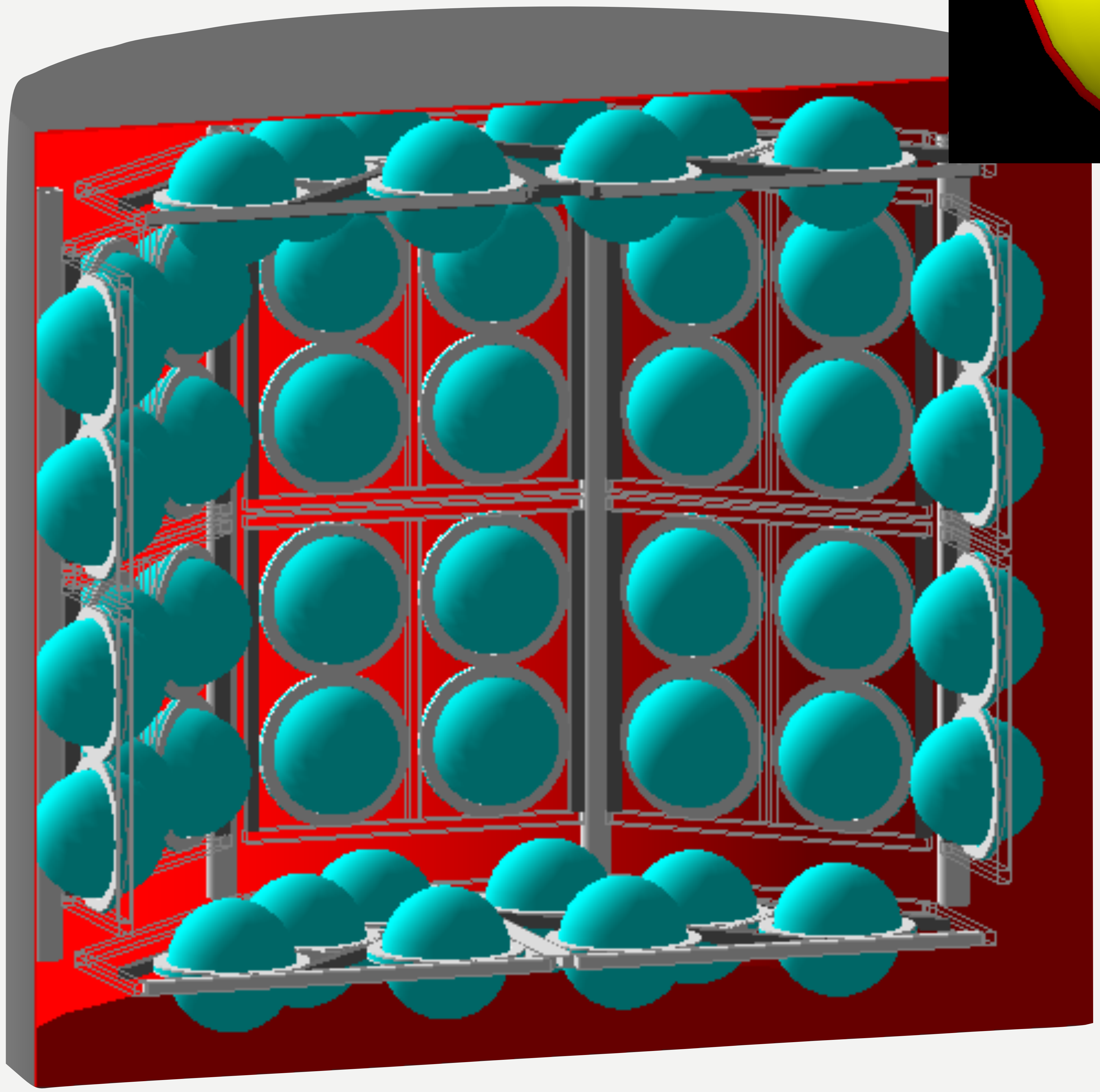
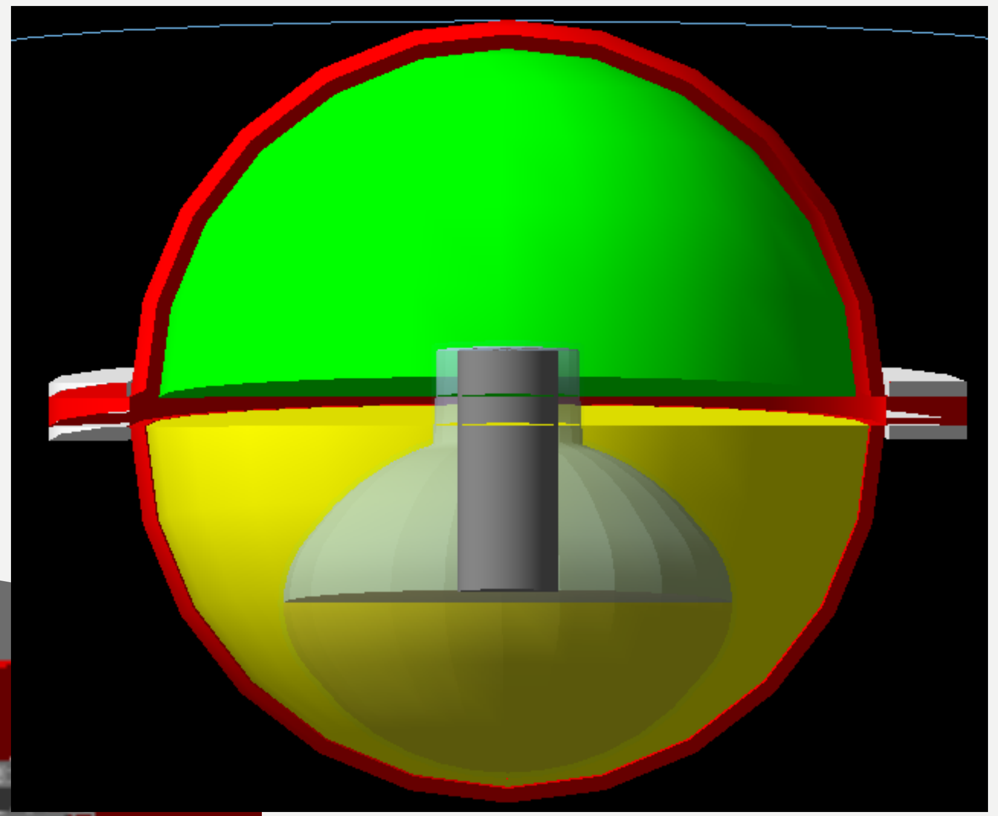
Simulation - RAT-PAC

Understanding our results

- Monte Carlo (MC) package for low energy neutrinos (MeV)
- Uses GEANT4, GLG4sim and CLHEP to simulate events
- Implemented detector geometries, PMT encapsulations and generators
- Output a file containing
  - hit
  - charge
  - time information (including dark noise (3 kHZ)
  - MC information





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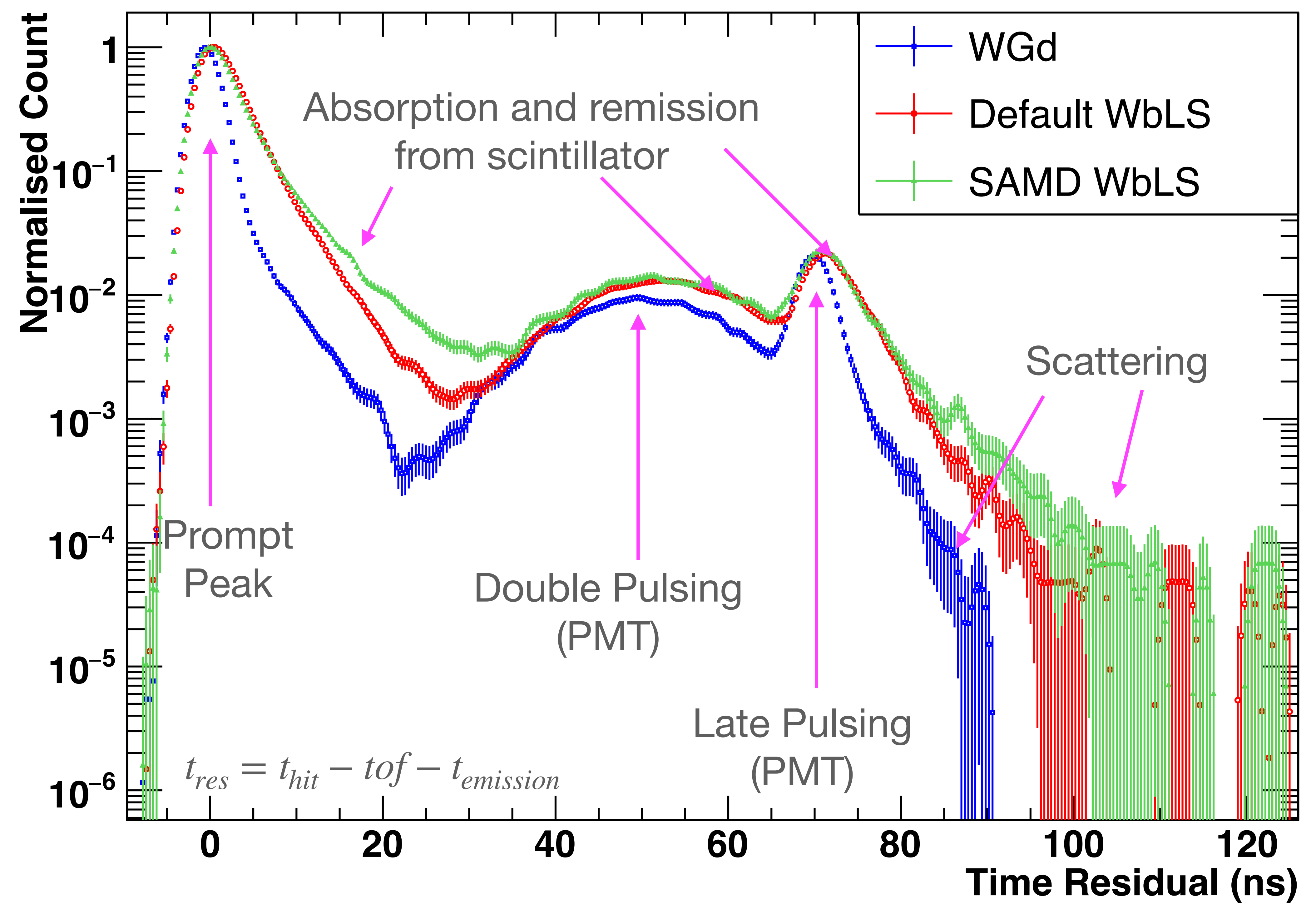
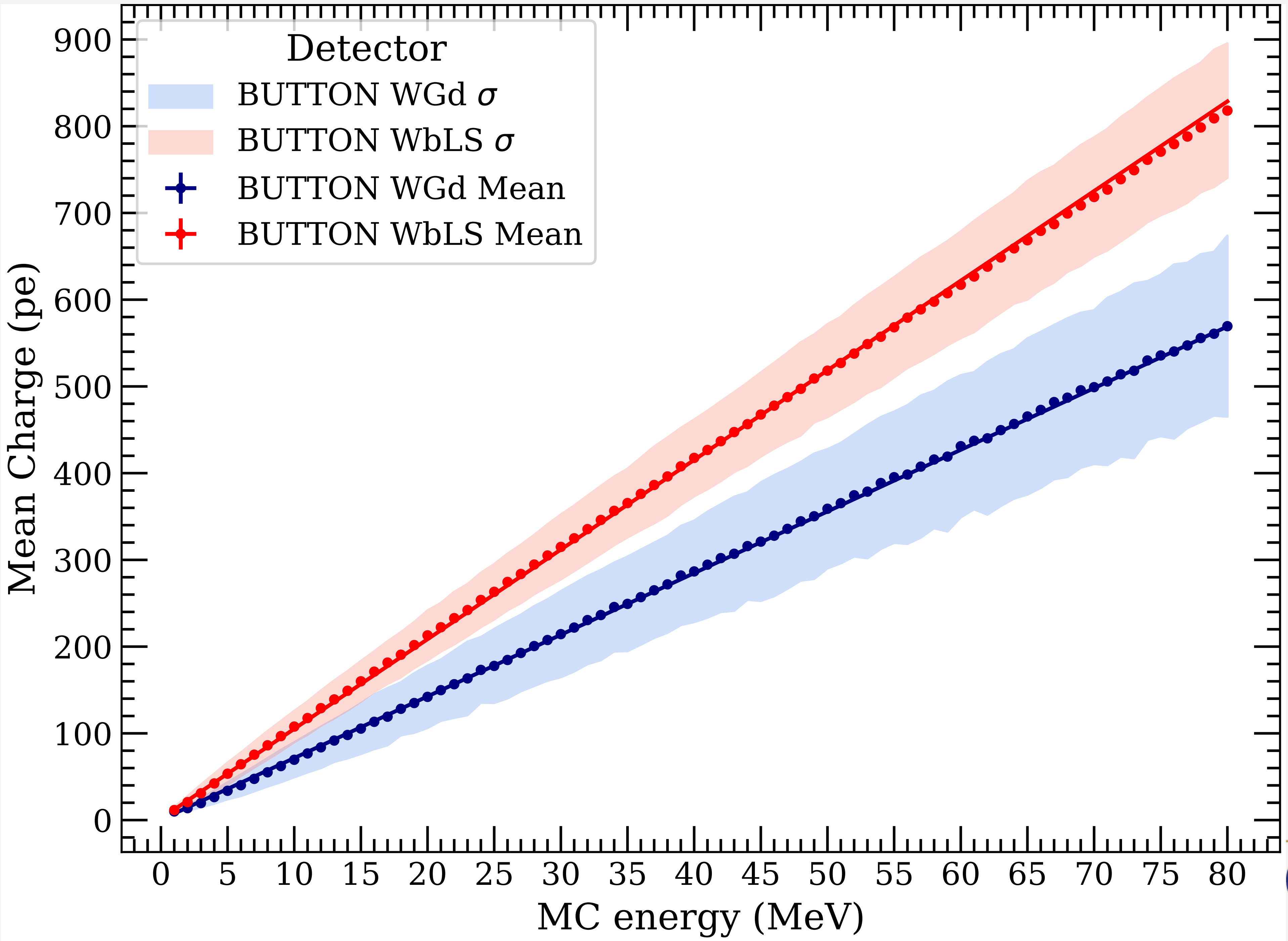
Reconstruction

Understanding our results

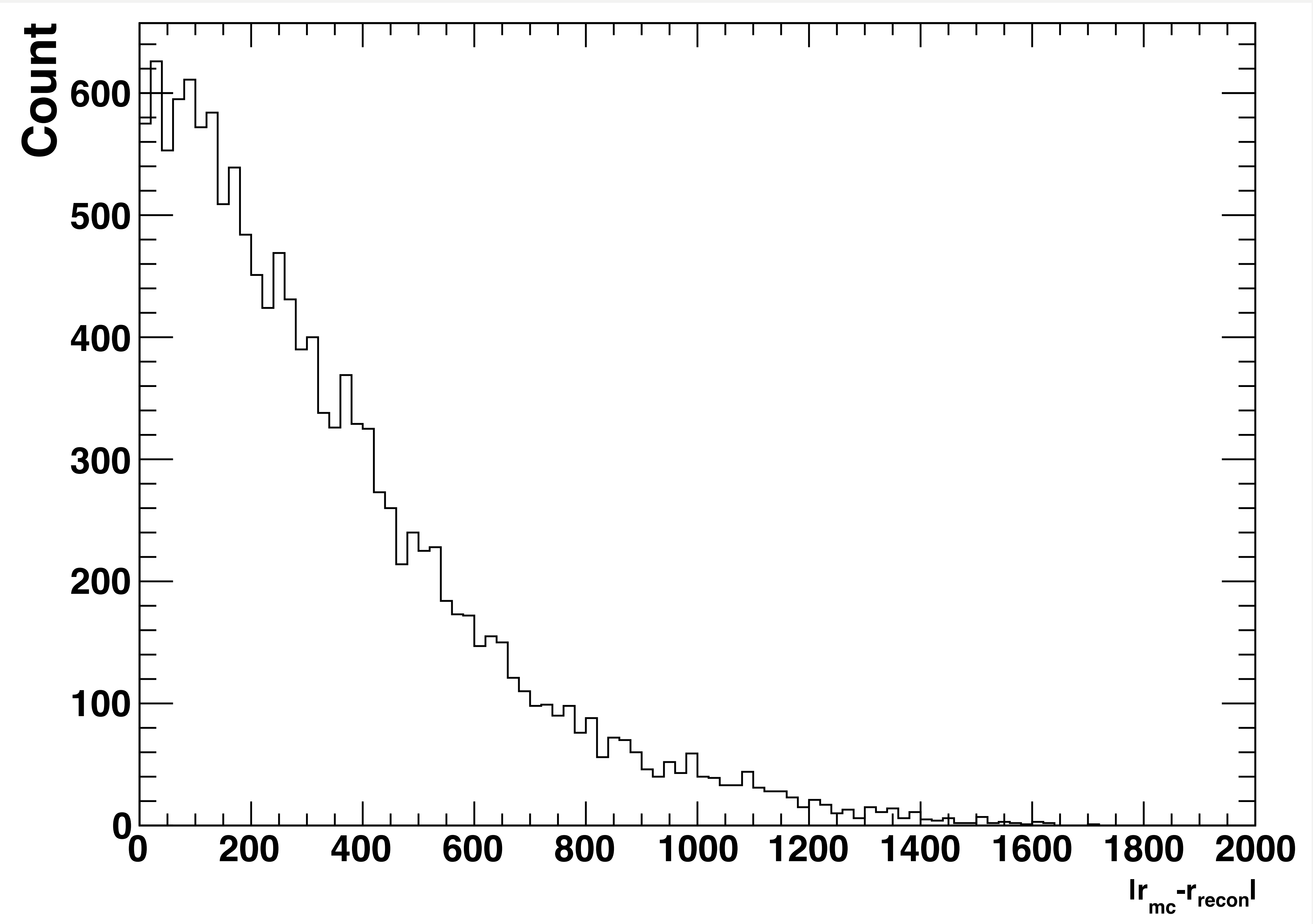
- Modified version of BONSAI (Super-K fitter)
  - Maximum-likelihood fitter to the timing and hit distribution
- Returns
  1. Charge
  2. Reconstructed position
  3. Monte Carlo parameters (energy, position, etc)
  4. Time between events
  5. Number of hits and so on



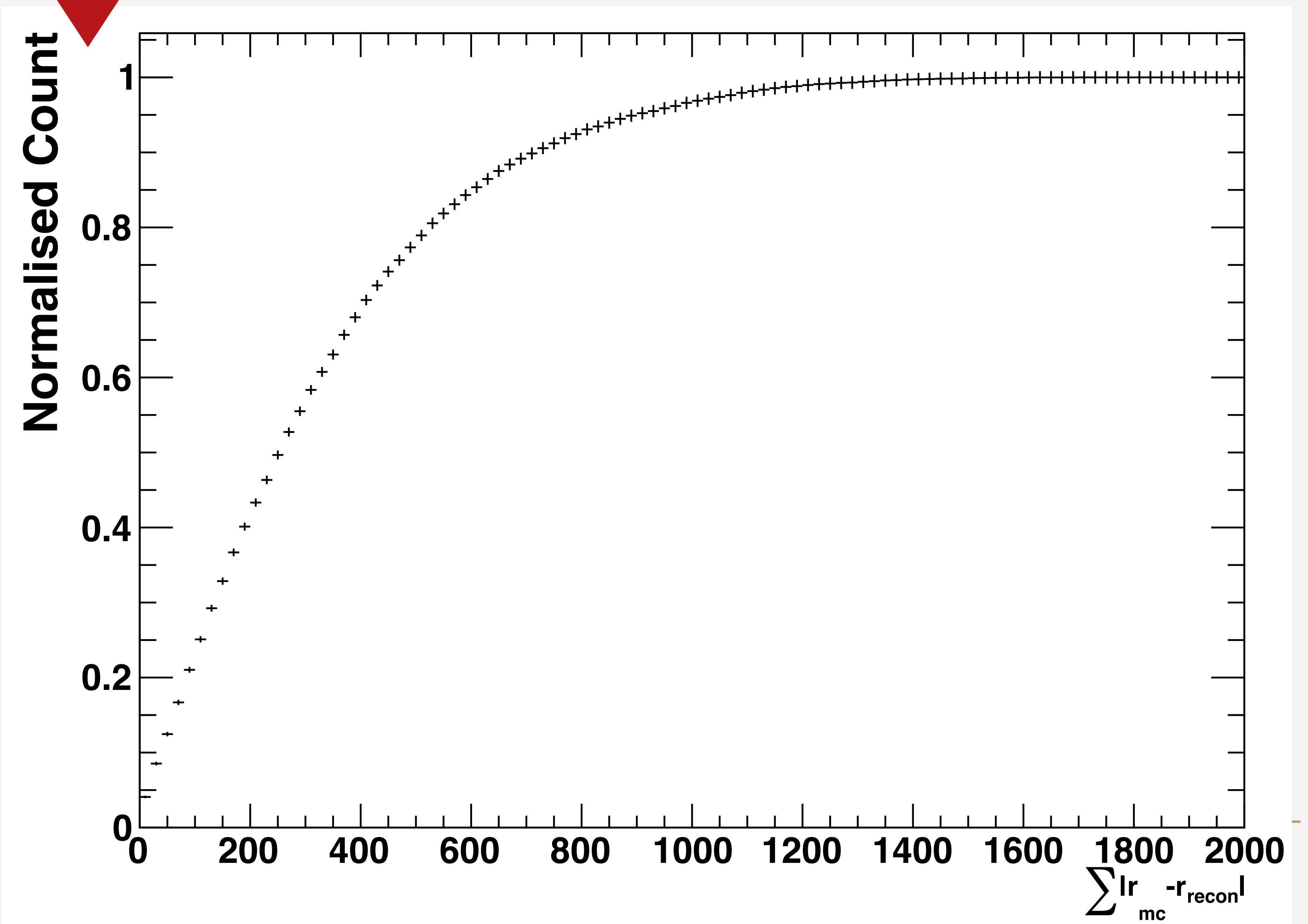


Vertex Resolution

- Similar method used by SK to determined the reconstruction resolution
- Compare the reconstructed vertex to the truth (MC) vertex
- Using the cumulative of $|r_{mc} - r_{recon}| <$ 68% (1 sigma)
- Higher values of vertex resolution denotes poorer vertex reconstruction



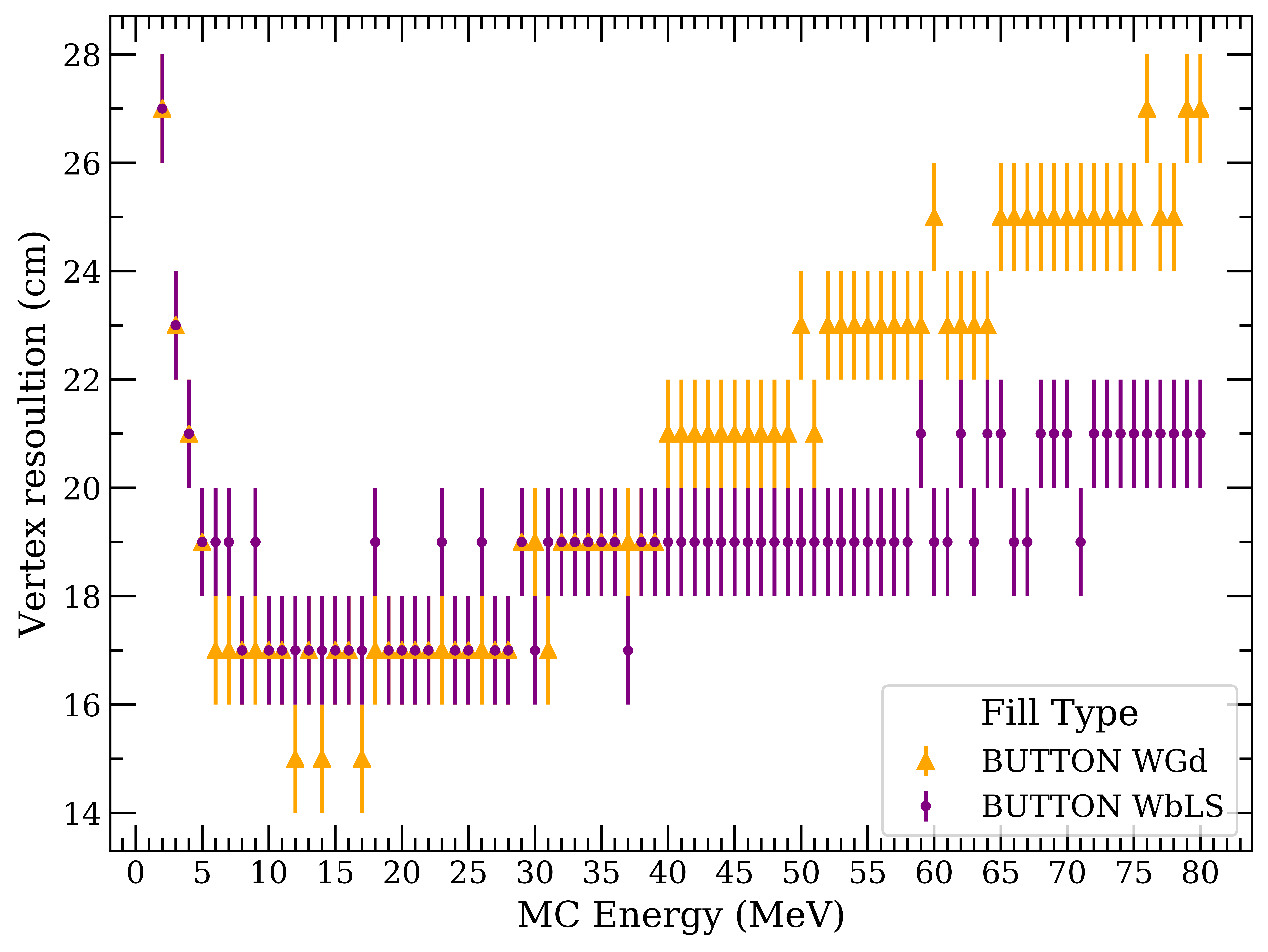
Cumulative distribution



Vertex Resolution

WGd and WbLS

- Vertex resolution improves to around 17 cm
- At 30 MeV the vertex resolution decreases in WGd
- This is less pronounced in WbLS
- Used to optimise Reconstruction



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Calibration Sources

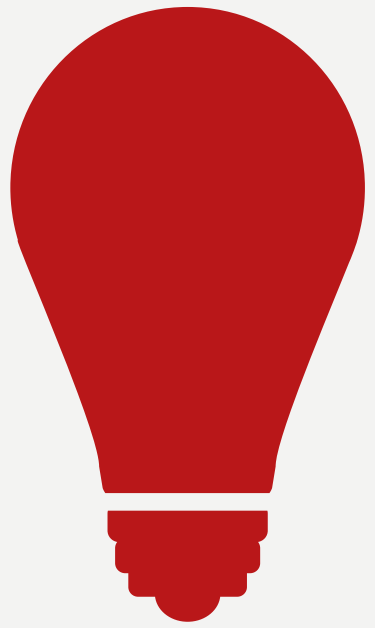
Use calibration sources to determine detector performance

Diffuser Cone

- Light cone with an opening angle of 40°
- Measures medium properties

Diffuser ball

- Light source of ‘uniform’ light
- PMT fast timing measurements



AmBe

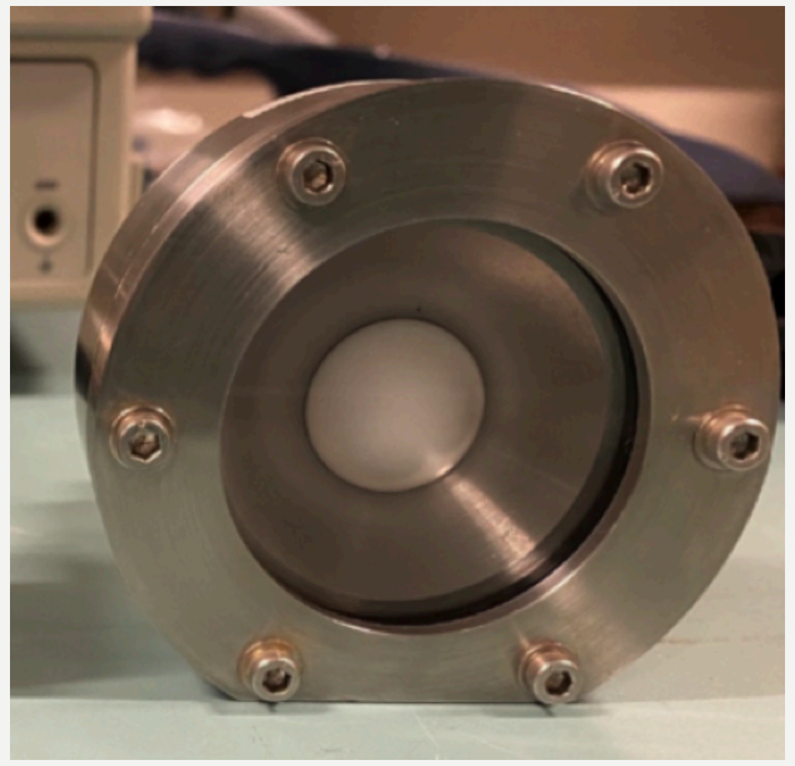
- neutron and correlated 4.4 MeV gamma source

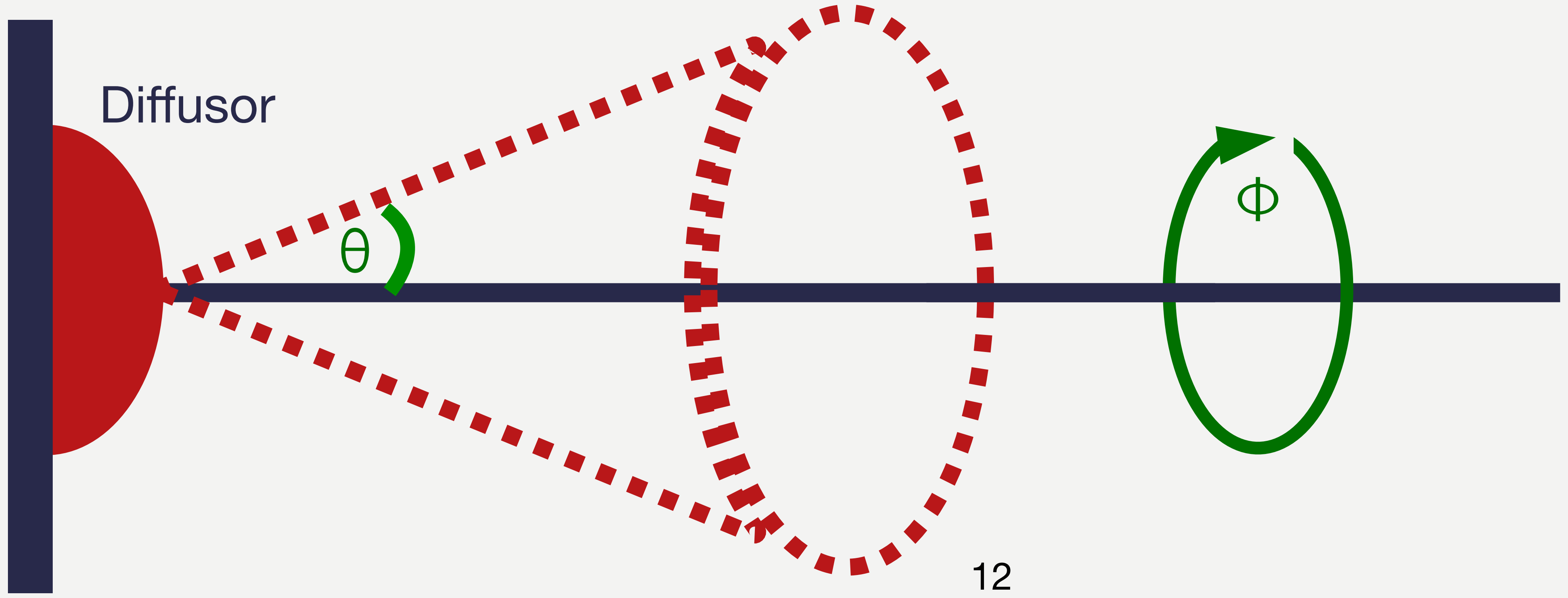
Radioactive source

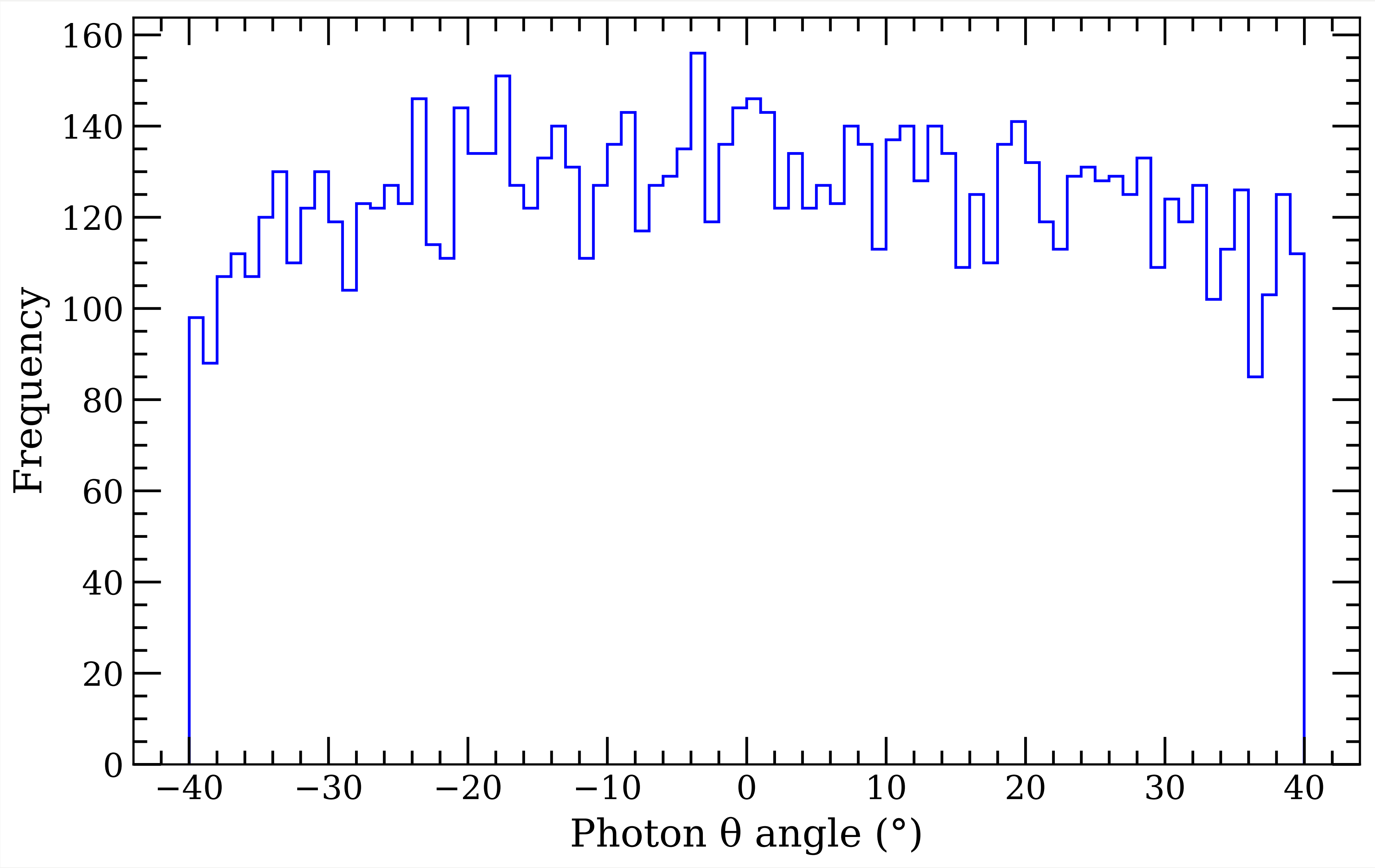
- Range of source for positioning and energy measurements

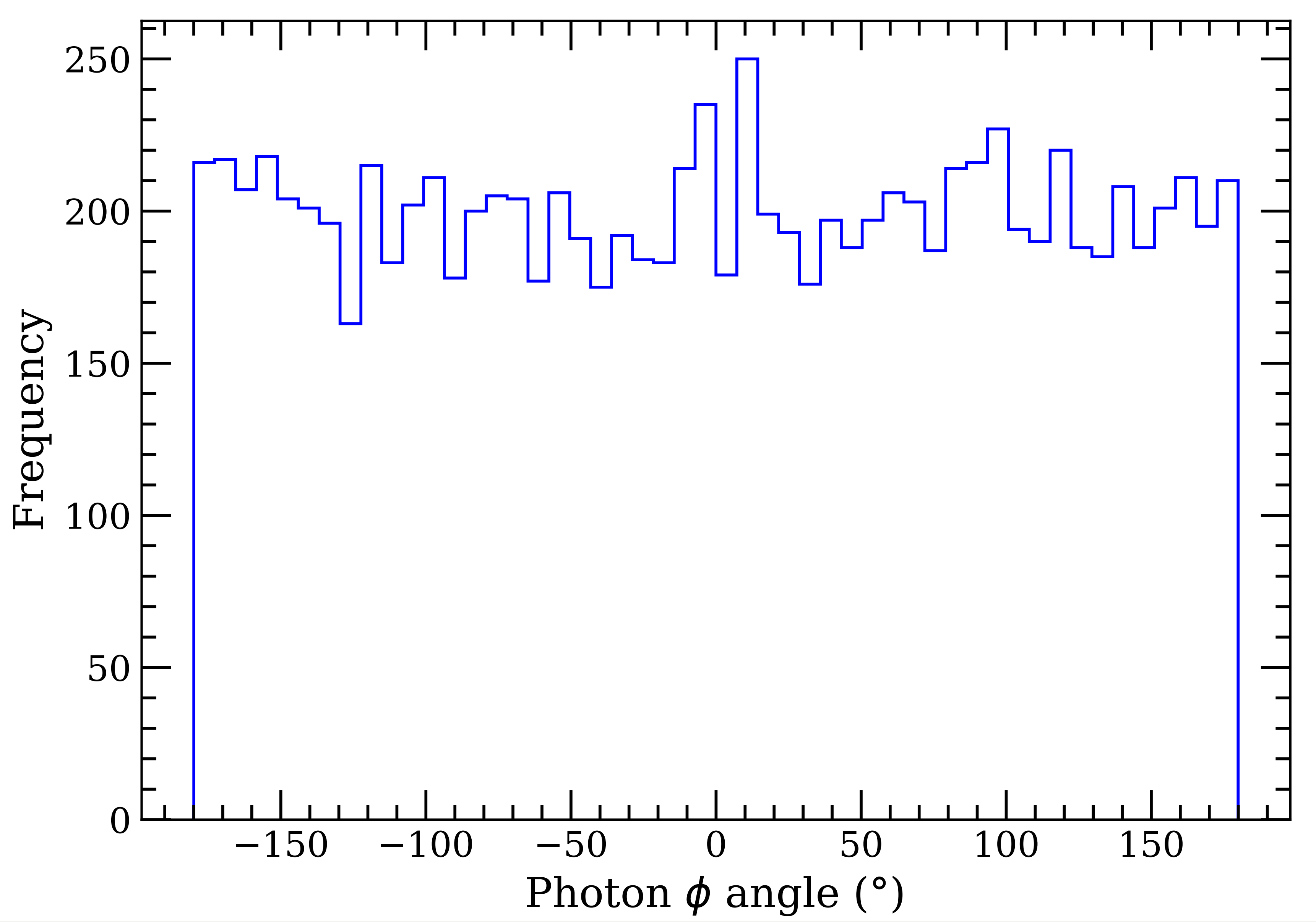
Diffusers in BUTTON

- BUTTON will use the same diffusers as Hyper-K
- Light cone with an opening angle of 40 $^\circ$
- Measure PMT characterisation and check water quality
- I have been developed a generator for simulations of diffusers









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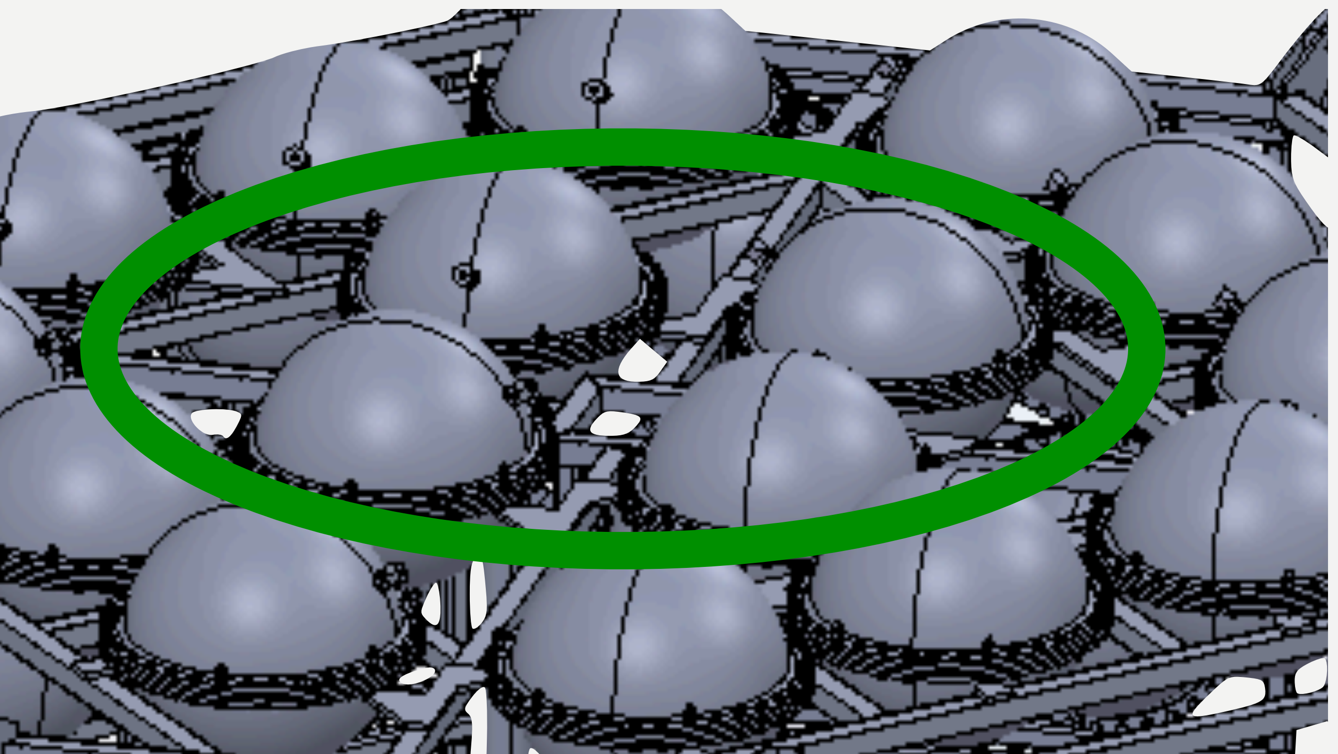
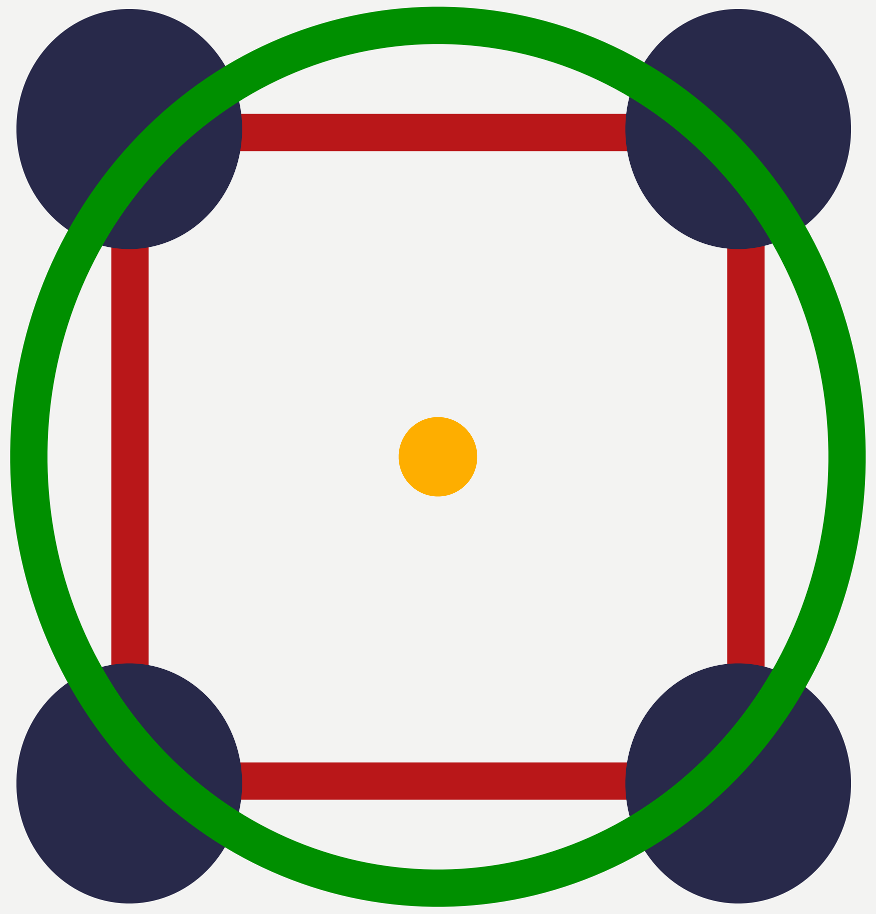
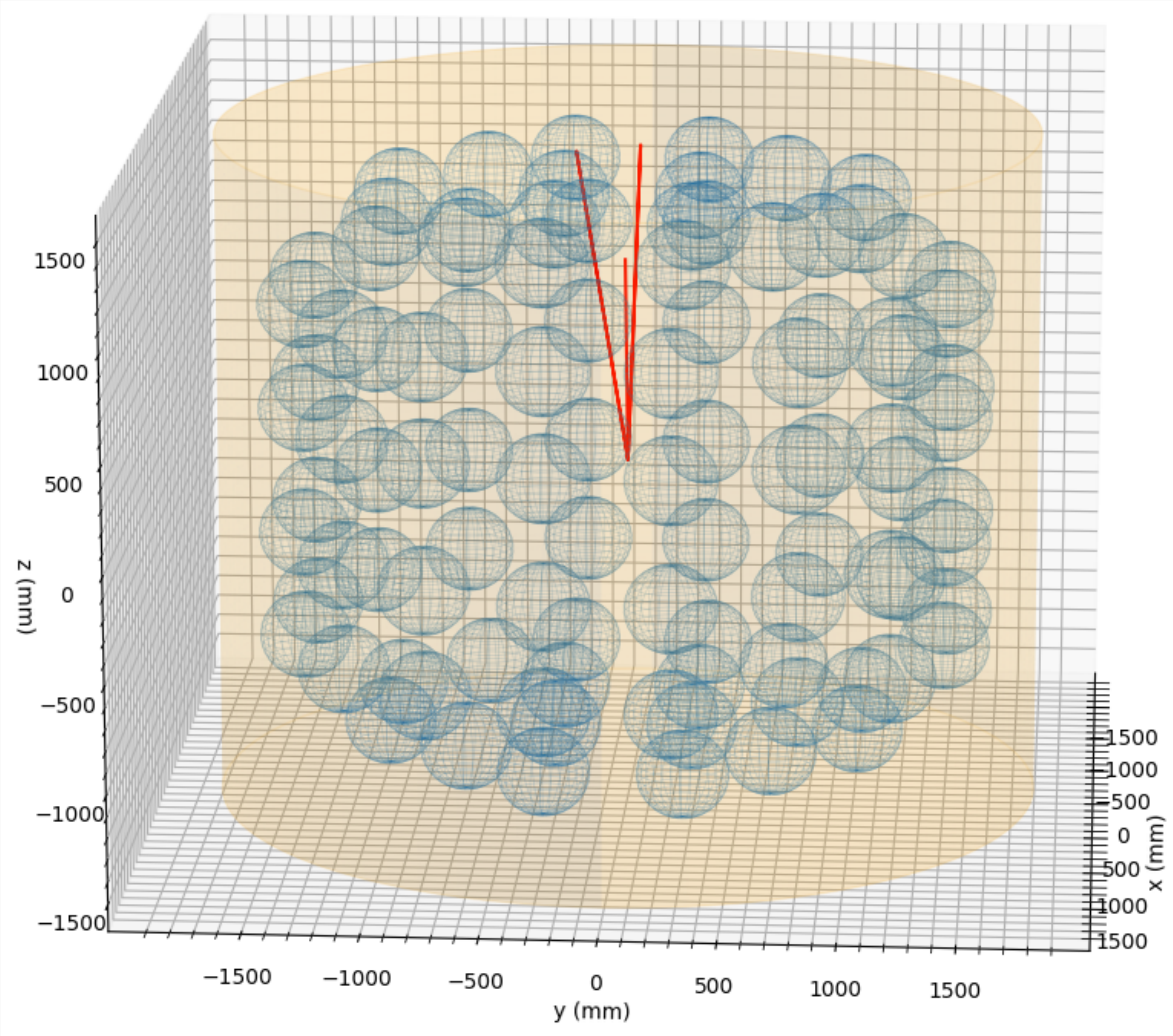
Vertical Diffuser

Debugging

- Need to verify the cone direction (40° is a wide angle = harder to determine cone position)
- From centre of tank fire photons vertically up
- Calculate angle need to hit only top 4 PMTs (~14-16°)
- See charge only on the top 4 PMTs







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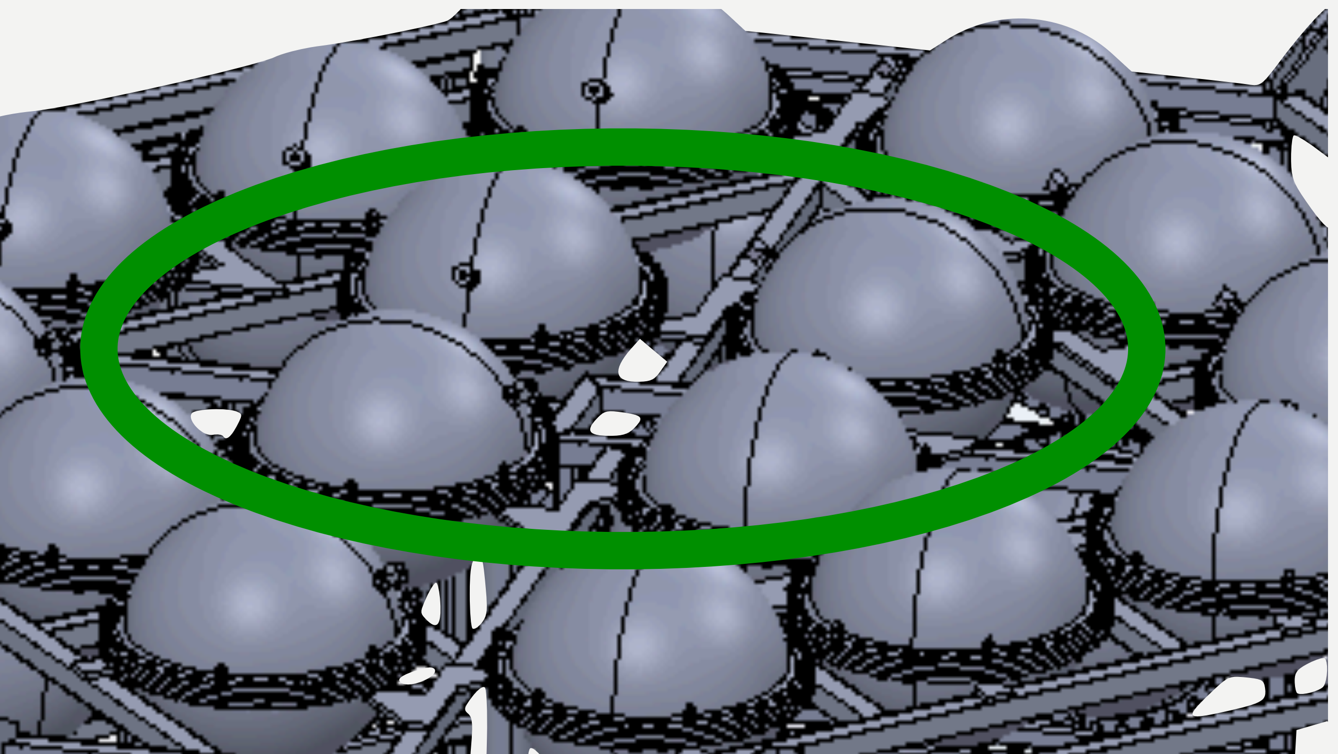

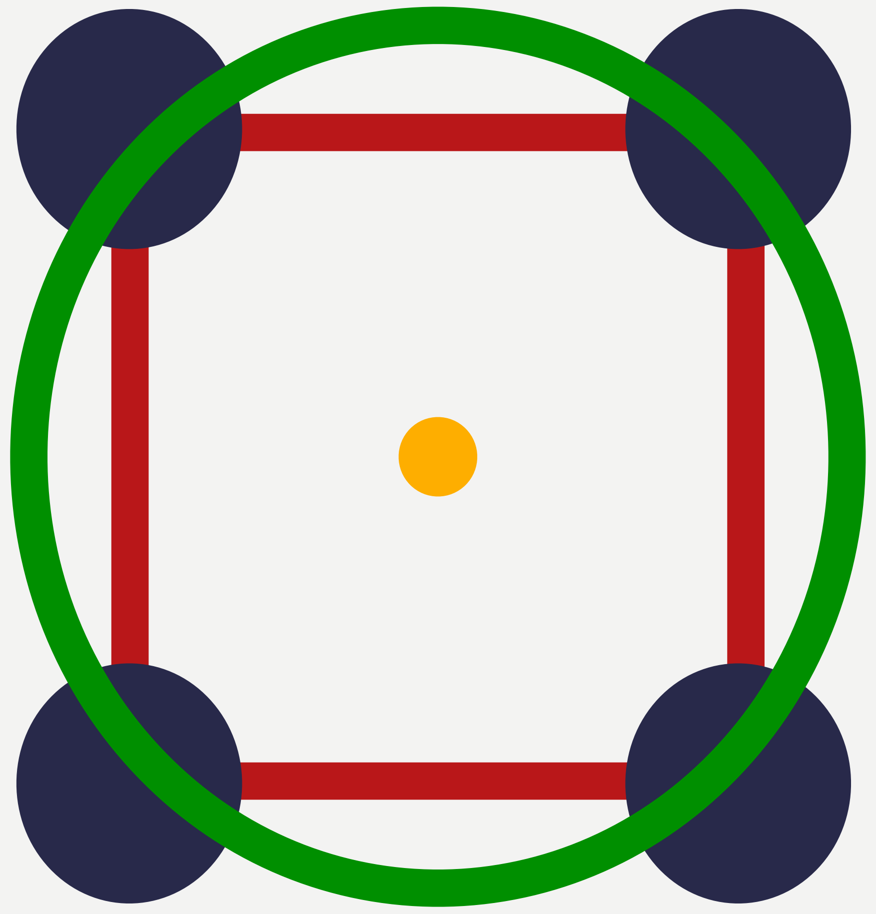

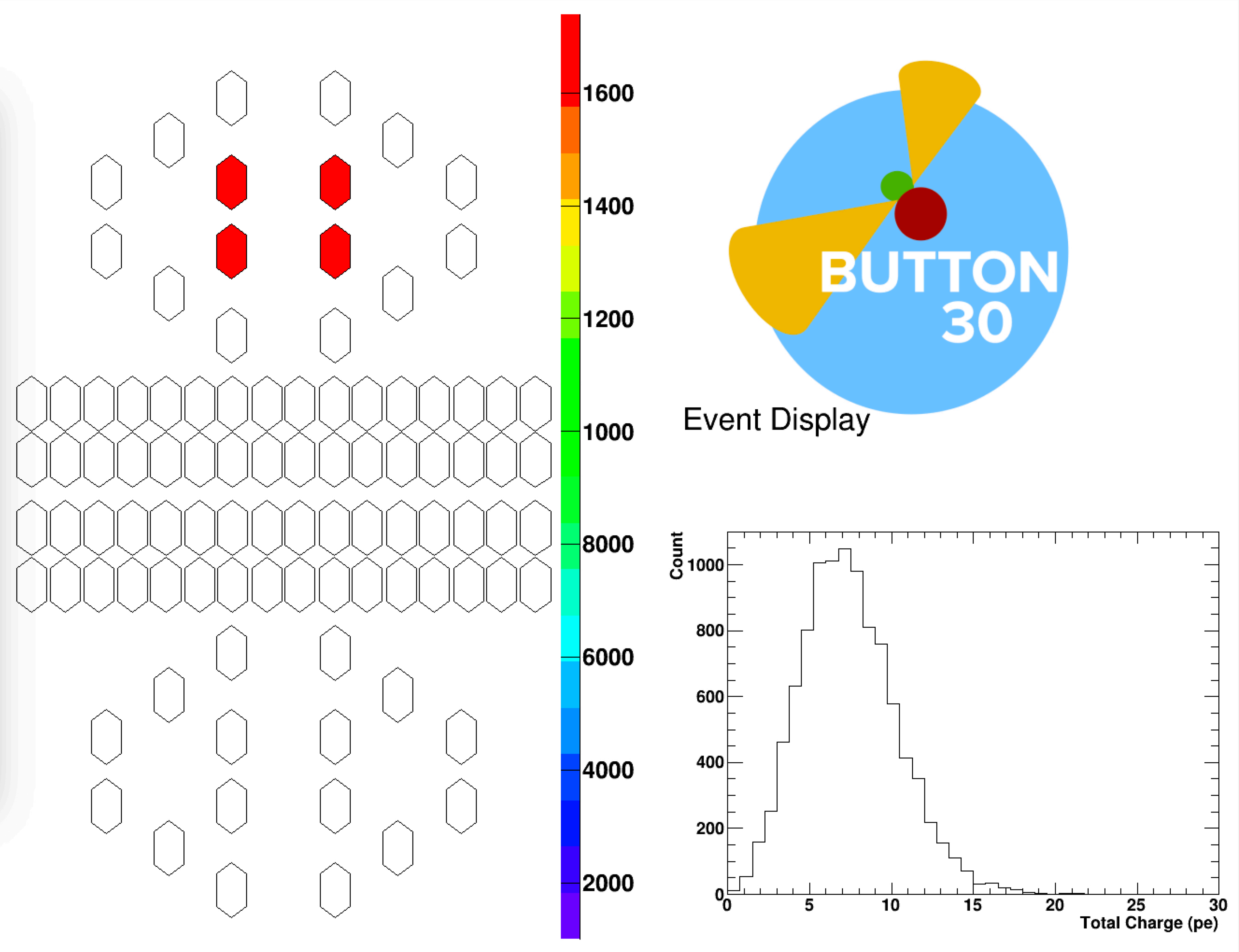

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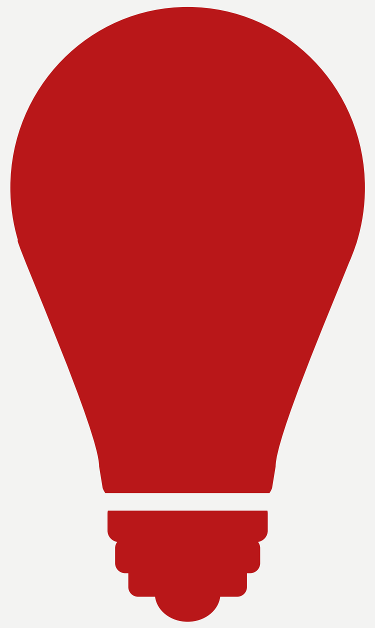

AmBe

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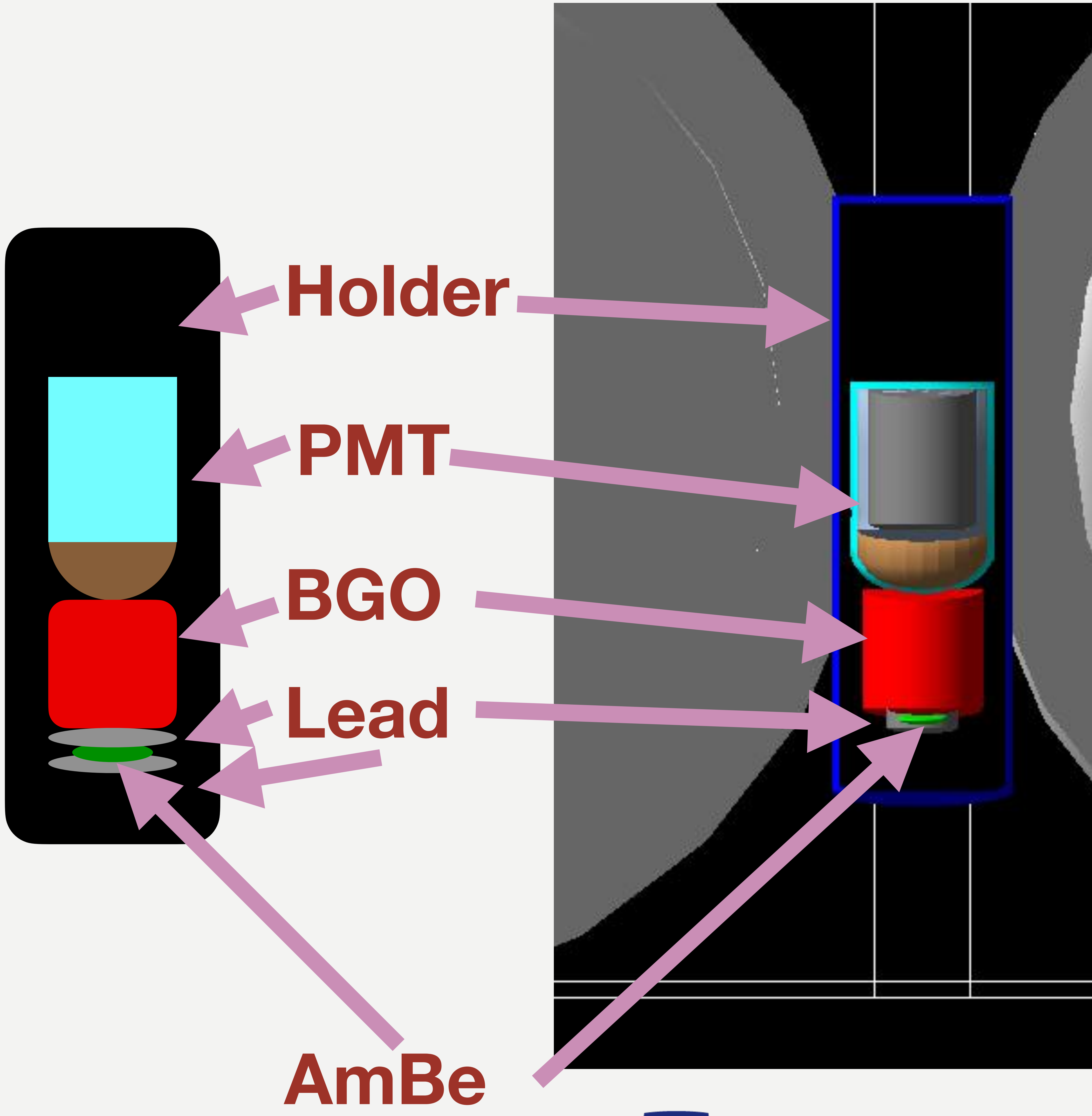
AmBe Simulation

Generator

- Developed a AmBe generator
- Made AmBe source holder in RAT-PAC
- Produce a 4.4 MeV gamma and a neutron
- Gamma is tagged
- Measure time between tagging and neutron capture
- The addition of gadolinium to water improve the probability of detection of thermal neutrons



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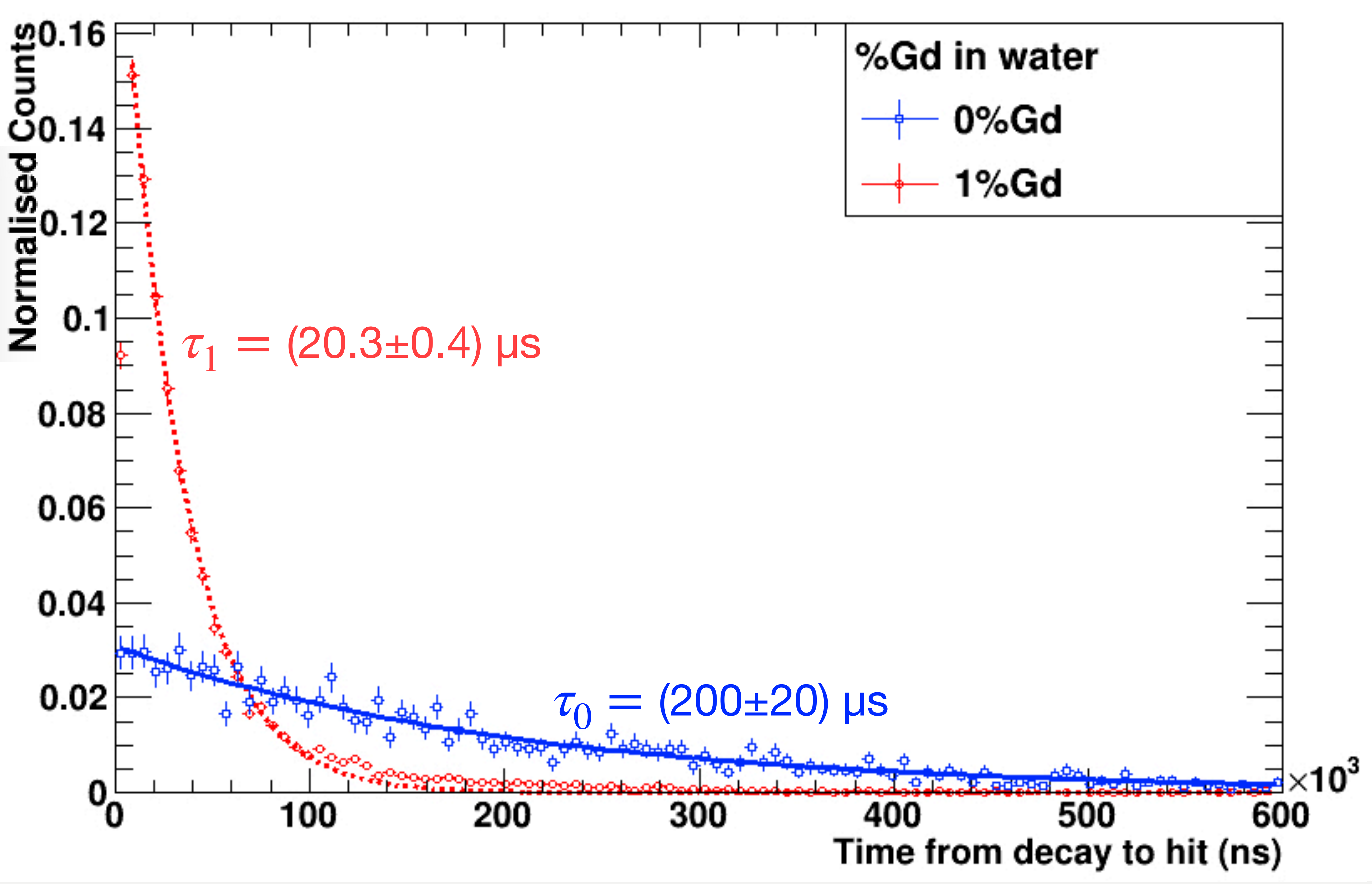
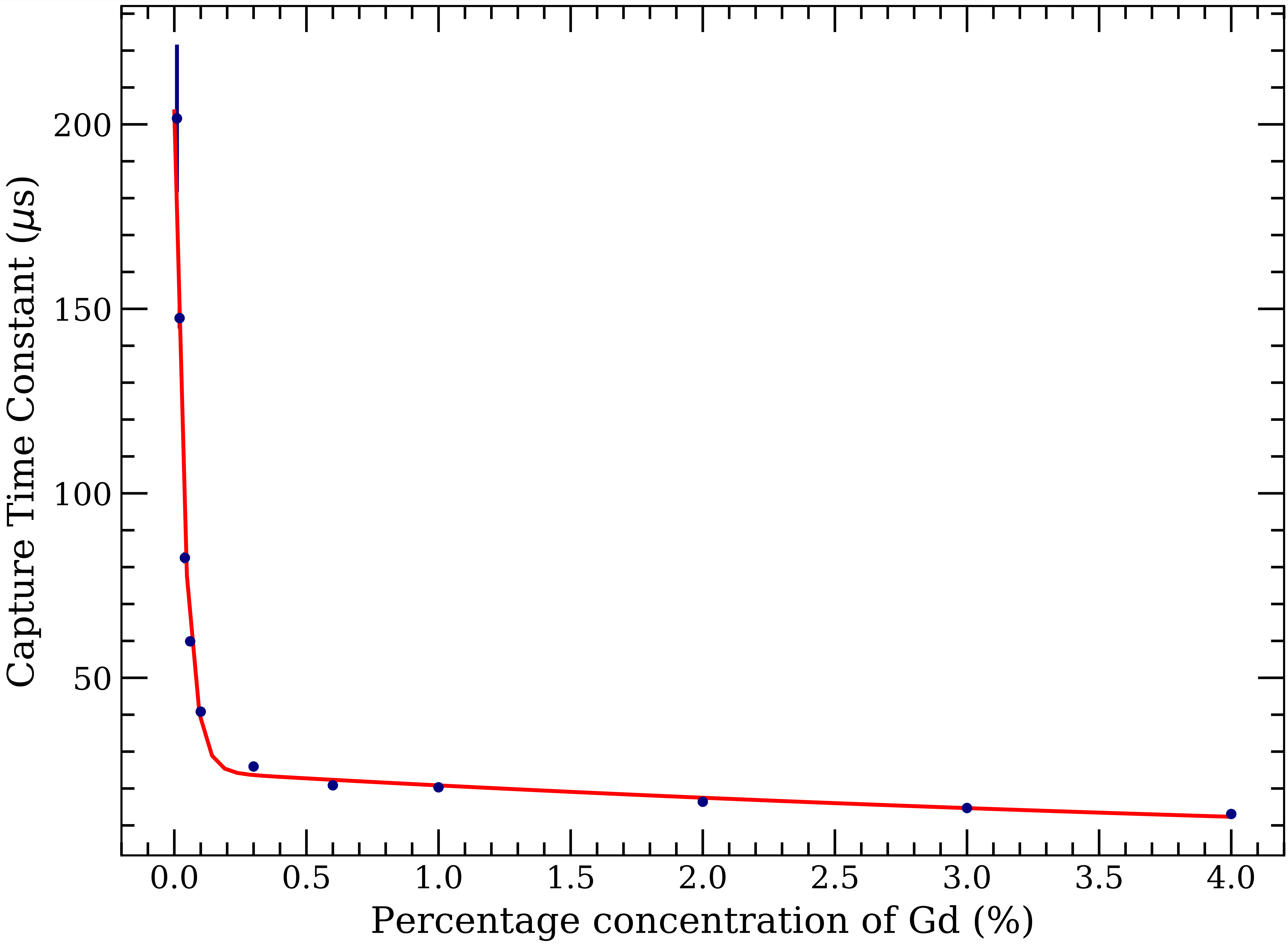
Capture Time

- Difference in time between tag and PMT trigger correlated to capture time



- Capture time constant can determine the % concentration of Gd



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Conclusions

BUTTON Future

- BUTTON currently under construction
- Expected first measurement (water) around Summer/Autumn 2024
- Deployment of WbLS 2025/2026
- These simulations will help to bench mark the detector performance
- Ongoing efforts accessing the next steps for the technology

Thanks for listening

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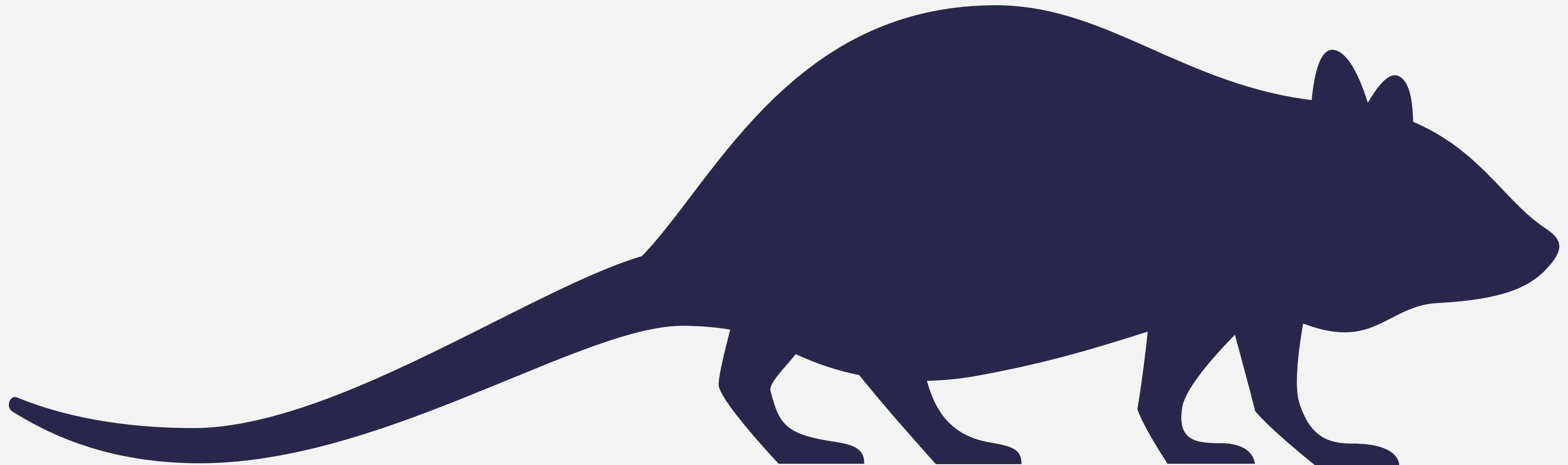
Back up

RAT-PAC

Our Monte Carlo Generator

- Our sequential Monte Carlo (MC) generator
- This made use of the work previously done on WATCHMAN
- Can be controlled using Macros that contain information about the required simulated event and a geo file with the detector information.
- Stores this information in ROOT containing (MC information, hit, charge and time information from the PMT (including dark noise (3 kHZ)))



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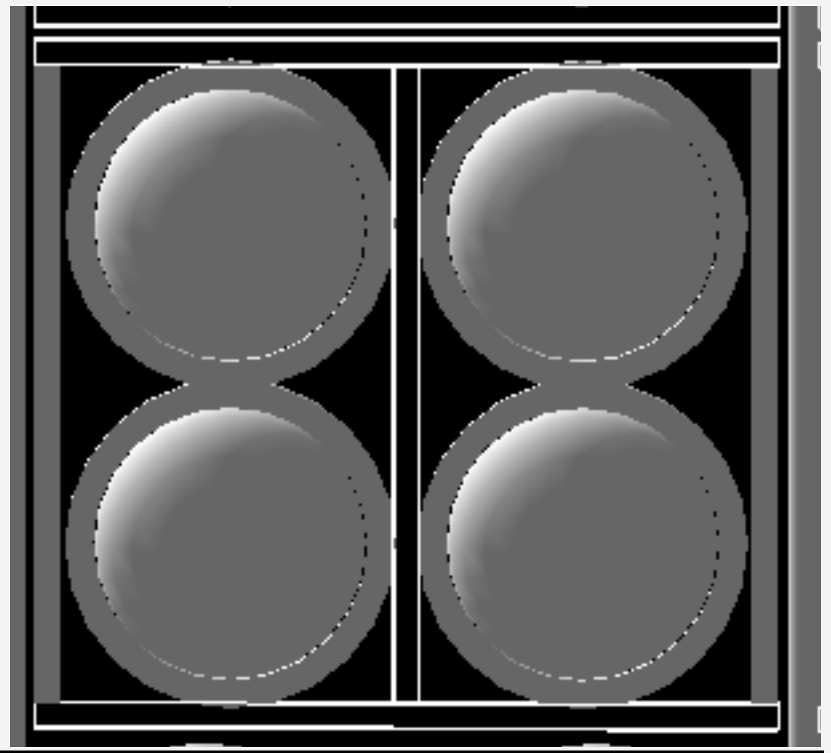
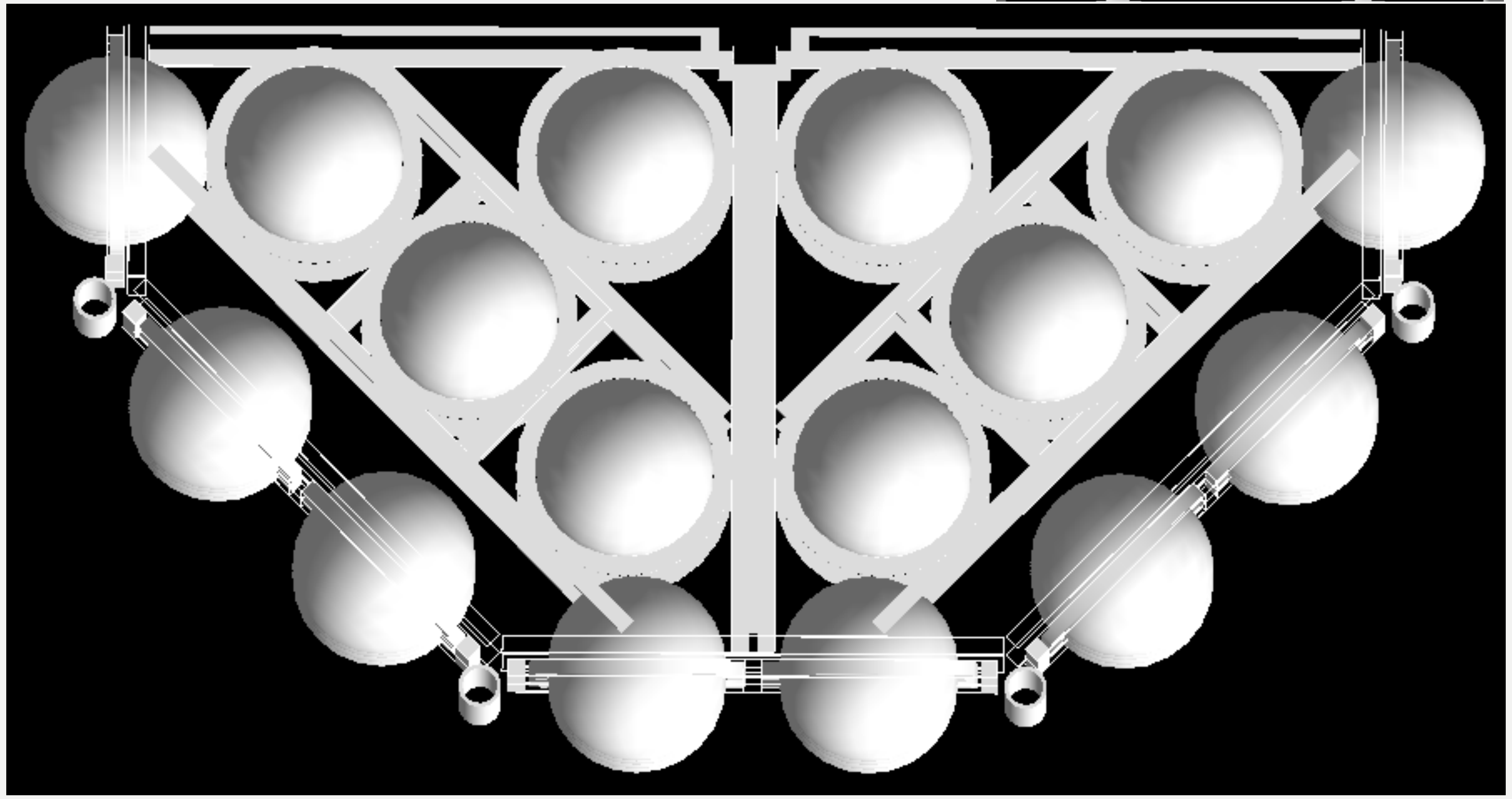
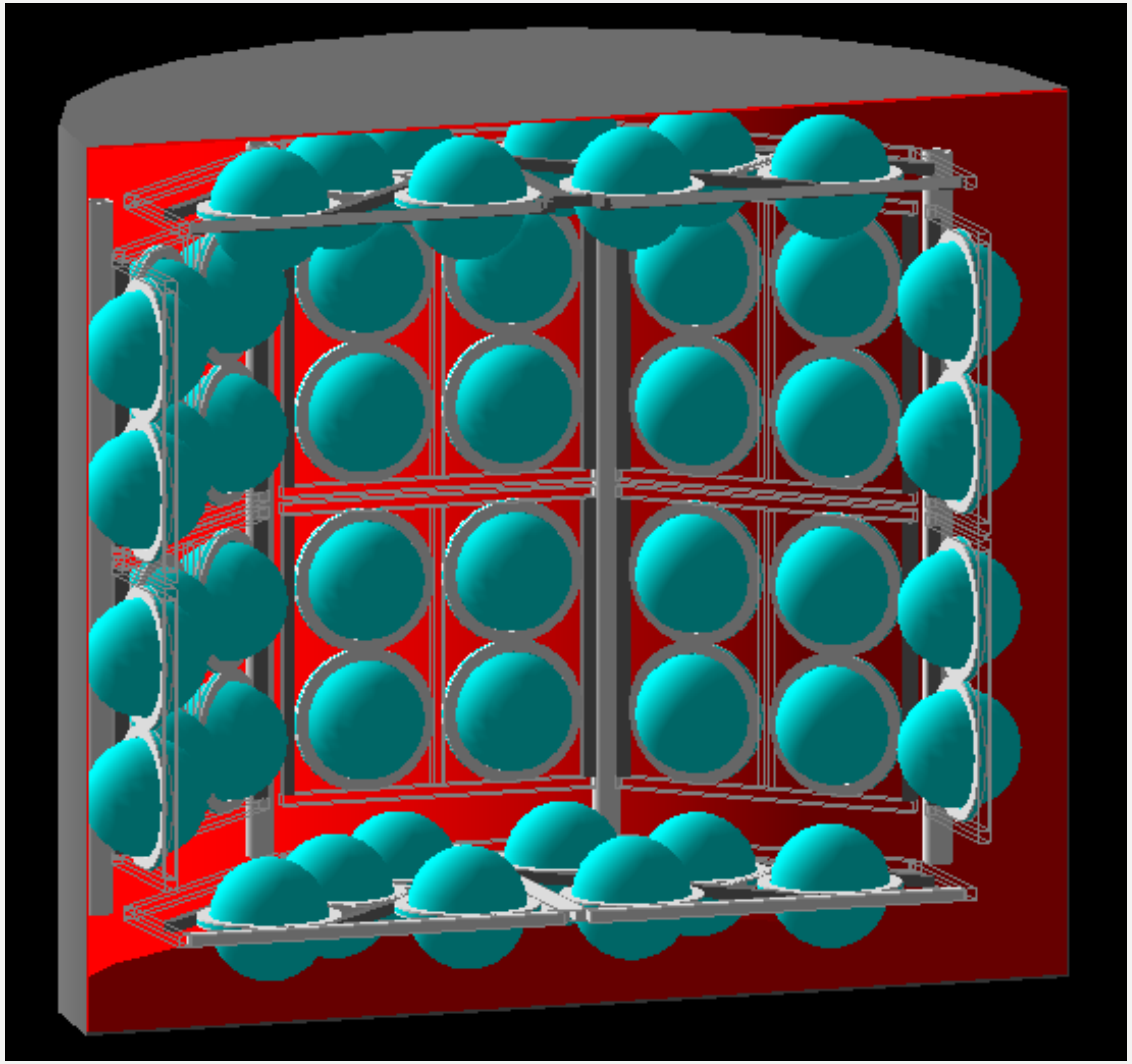
BUTTON Geometry

A full model of BUTTON

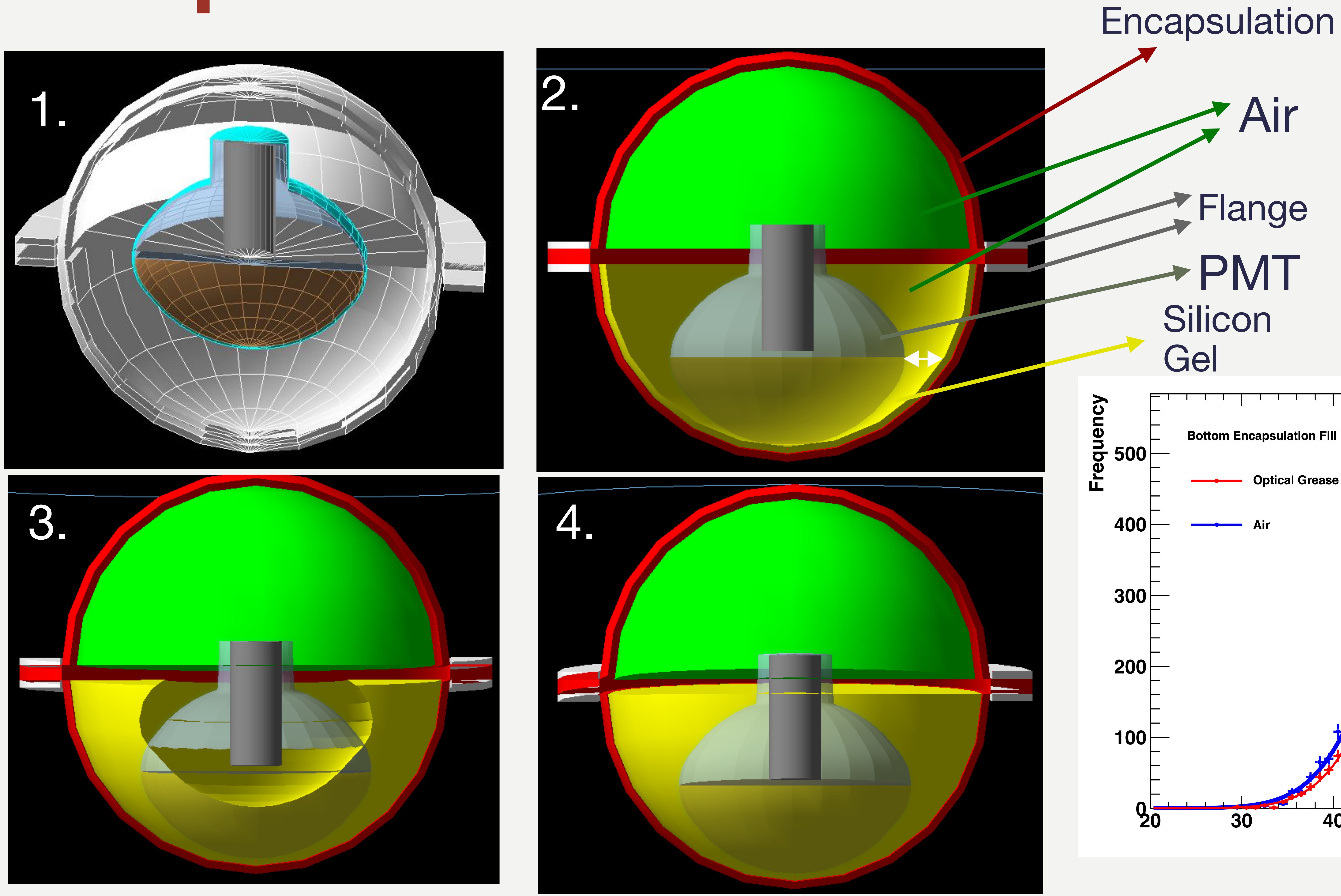
- The Frame made of series of repeating sections



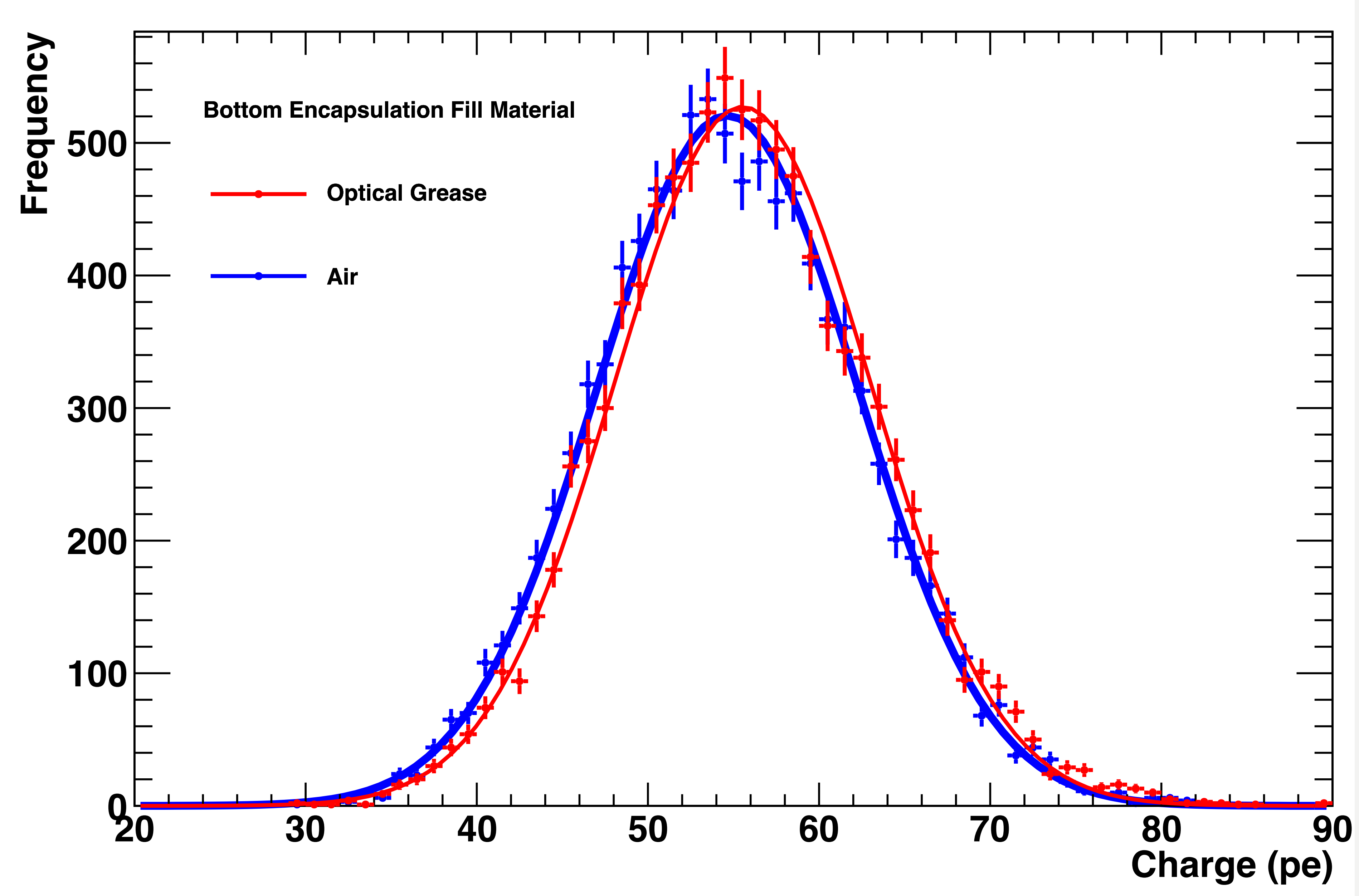




Encapsulations



- Encapsulations initially had PMT in the middle
- PMT moved to 5 mm gap
- This resulted in a small air gap



FRED

Reconstruction of Simulations

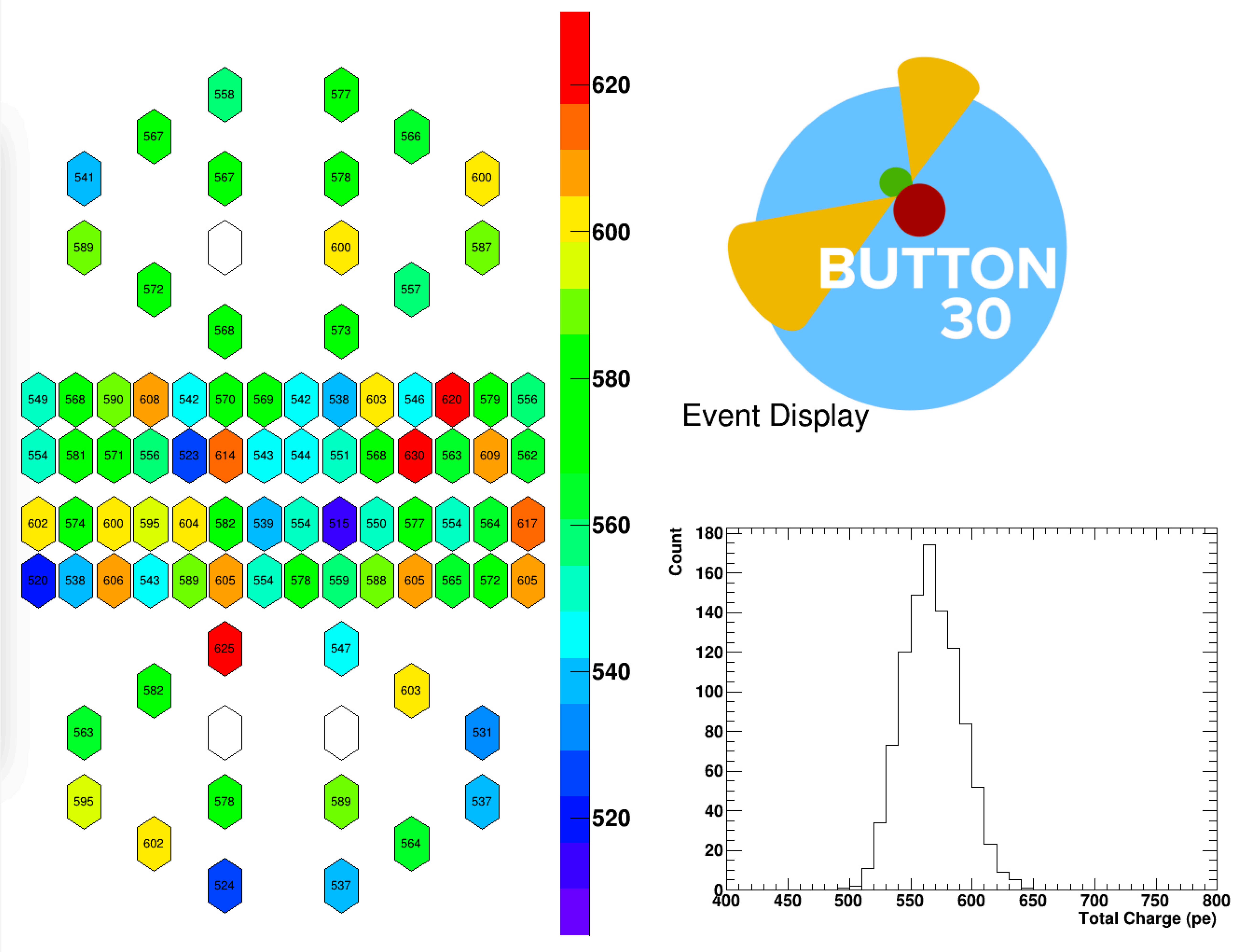
- Modified version of BONSAI (Super-K fitter)
    - Maximum-likelihood fitter to the timing and hit distribution
- Can change initial fitting parameters and inputs such time windows and search radius

- Returns a root file containing
    1. Number of hits (n9)
        - The number of pmt hits in a 9 ns time window, maximised for vertex
    2. Reconstructed position
    3. Monte Carlo parameters (energy, postion, etc)
    4. Time between events
    5. Charge and so on

Reconstructed Event Display

With logo

- Developed an event display for debugging (can be adapted for live event display)
- Top and bottom is shown in x and y
- Barrel is unfurled so that it is the solid angle and z
- Shown is a simulation of 10,000 optical photons uniformly from centre of tank



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Water based Liquid Scintillator (WbLS)

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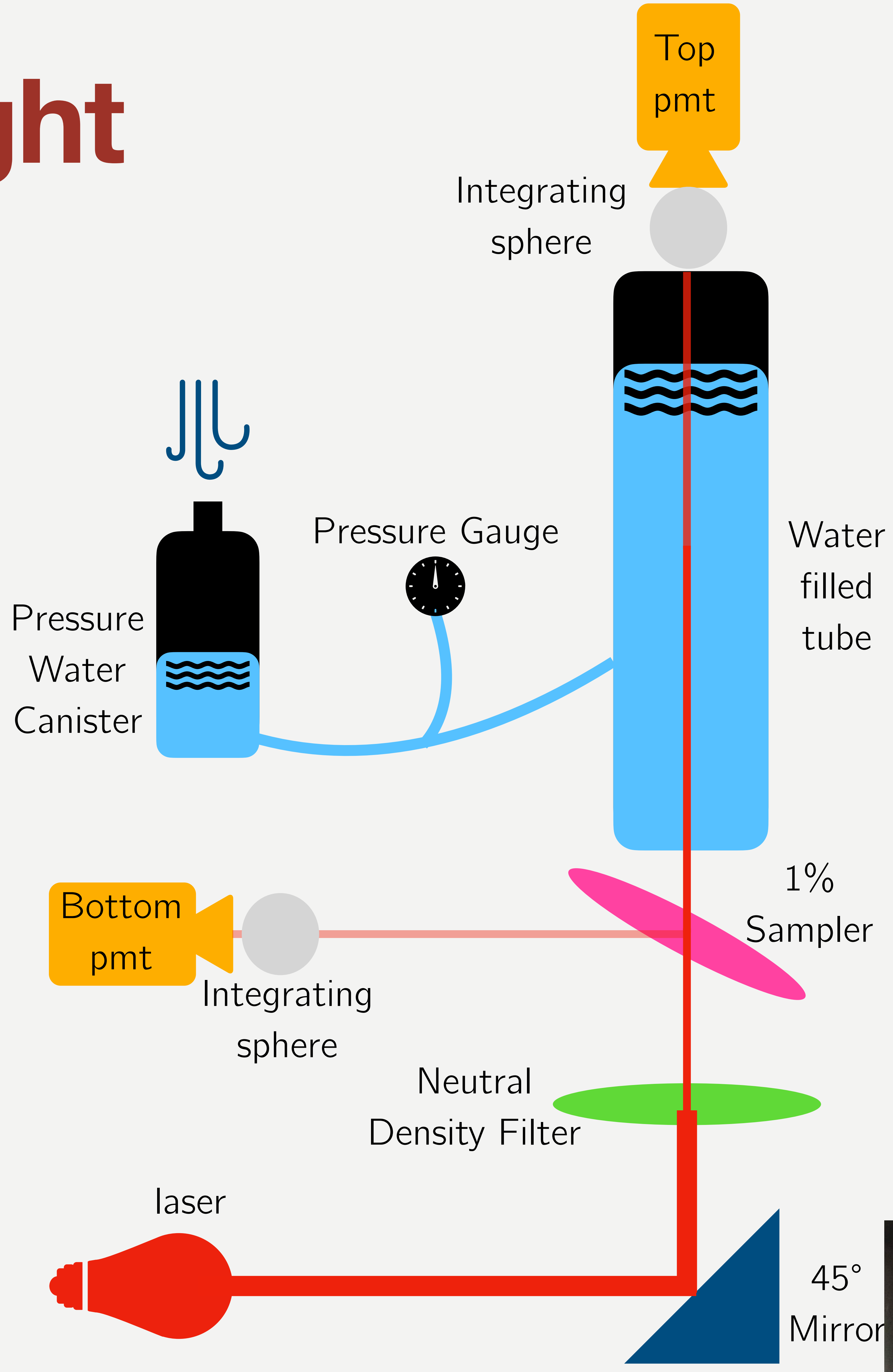
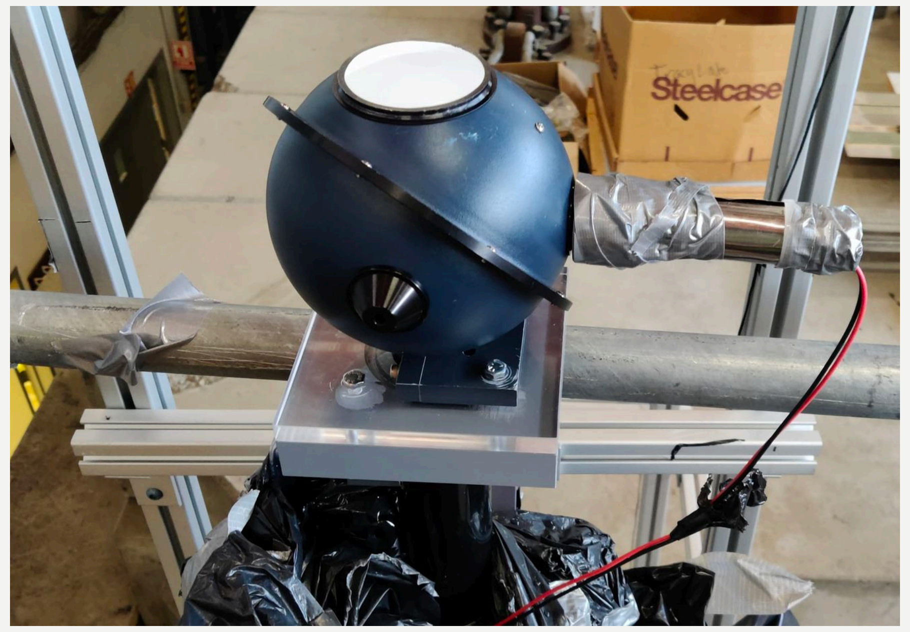
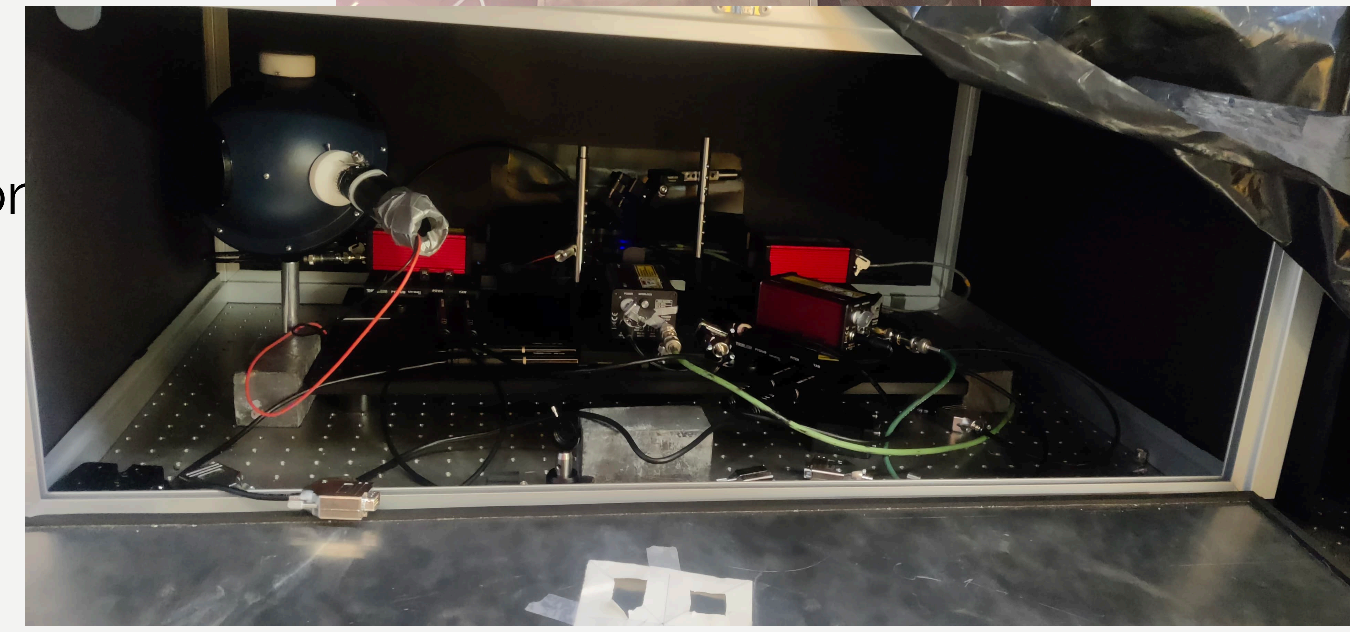
The Attenuation of Light

Doing the Dirty Work

- Scattering and Attenuation Measuring Device (SAMD)
- Want to measure the attenuation of light in WbLS to improve simulations
- Important for our simulations and systematic uncertainties







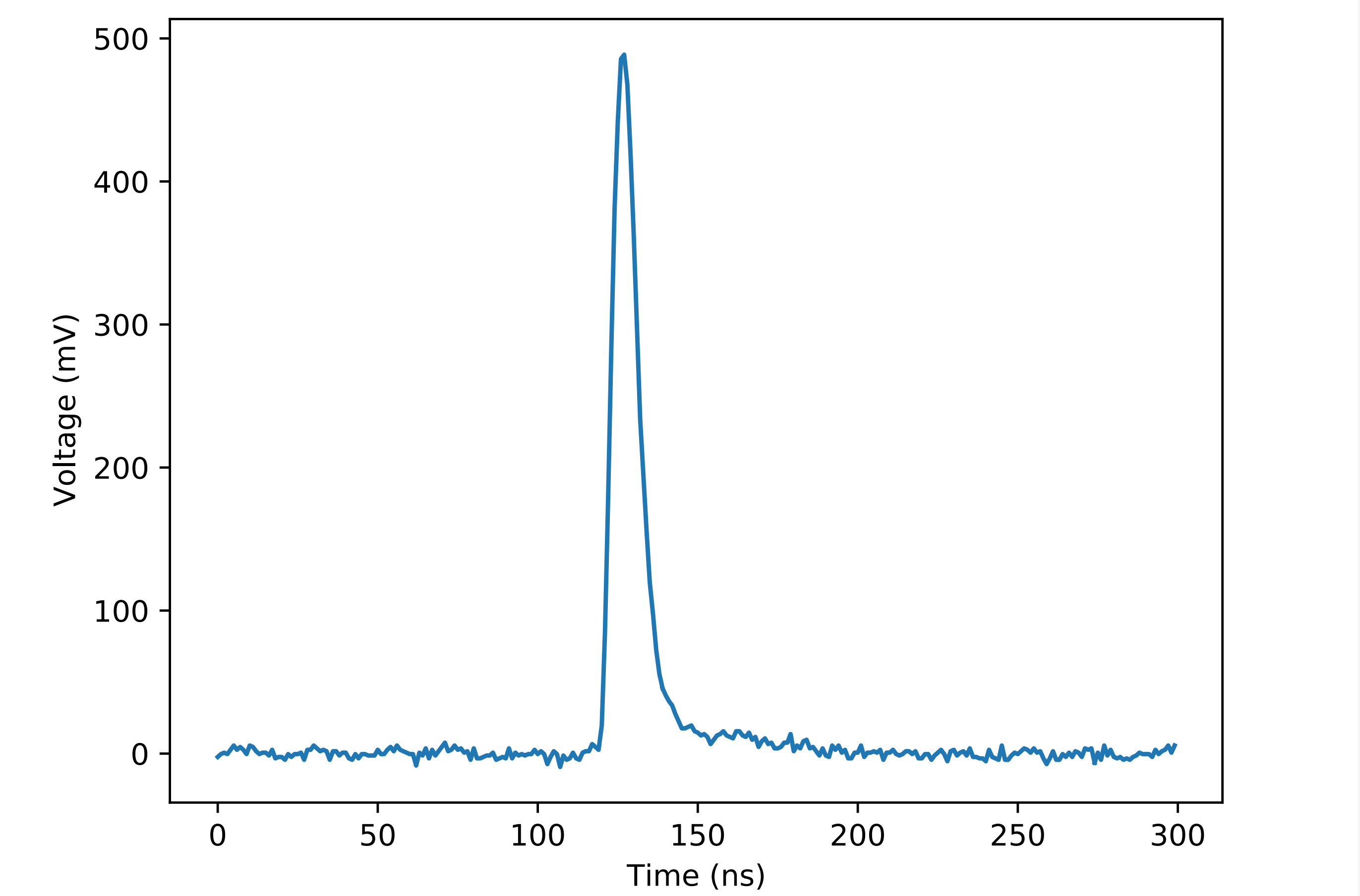
Measuring the Attenuation

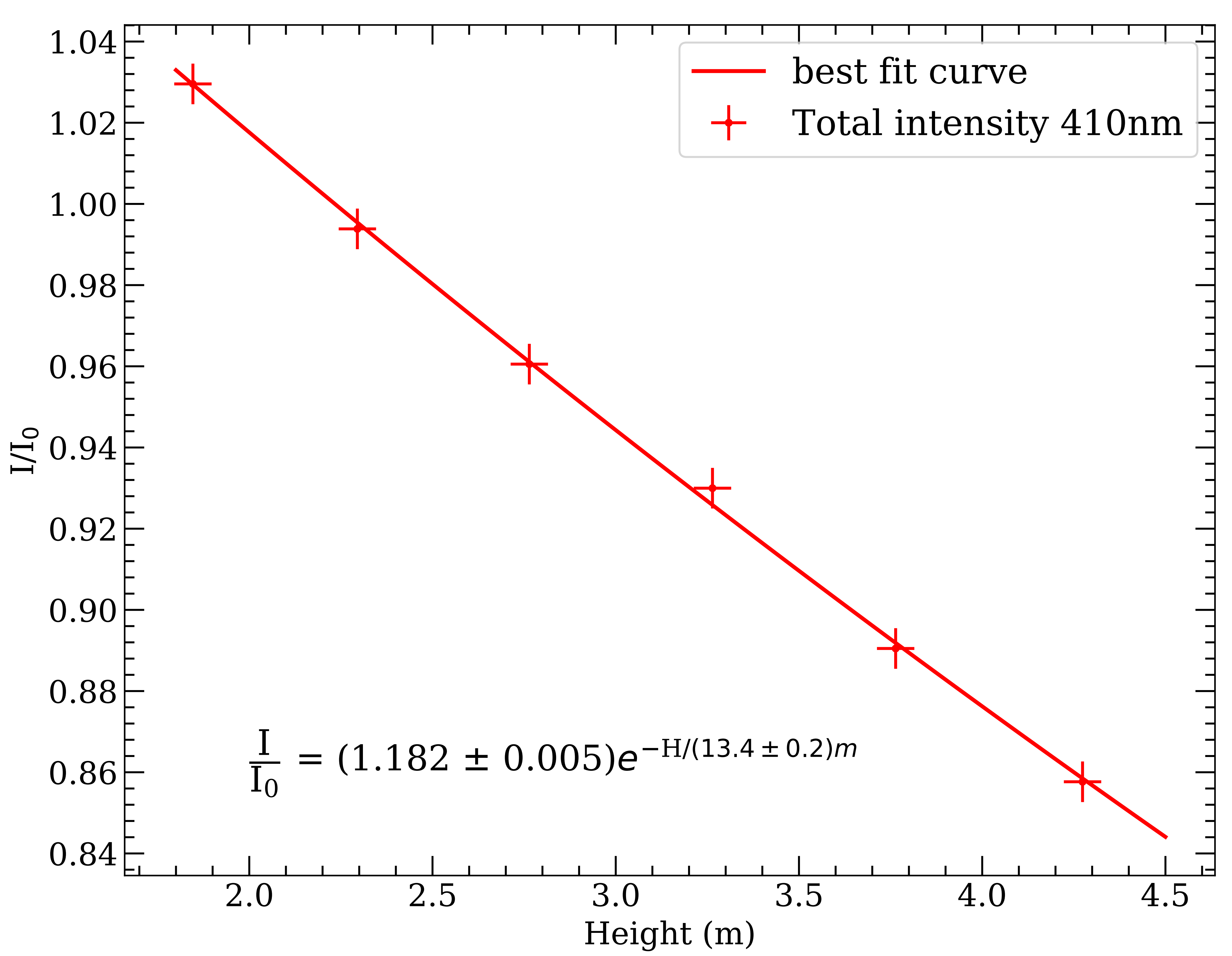
410 nm WbLS

- Integrate over the peak to get intensity
- The ratio of top to bottom PMT is taken as a function of height
- Orthogonal distance regression is used to fit an exponential to the data

$$\frac{I}{I_o} = \epsilon e^{\frac{-H}{z}}$$

- This system could be used in WbLS detectors like BUTTON





Data taken at UC Davis

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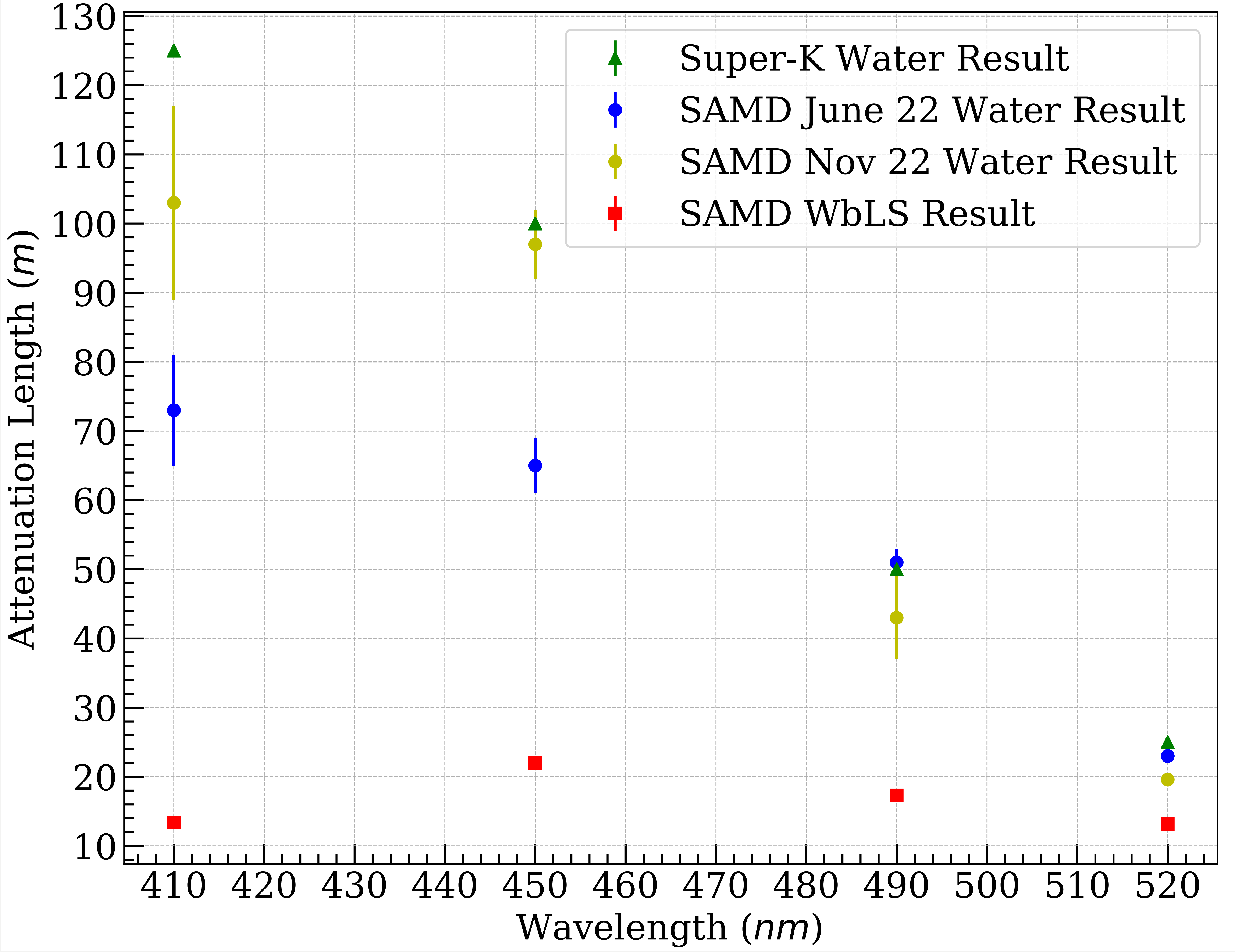
Attenuation Coefficient



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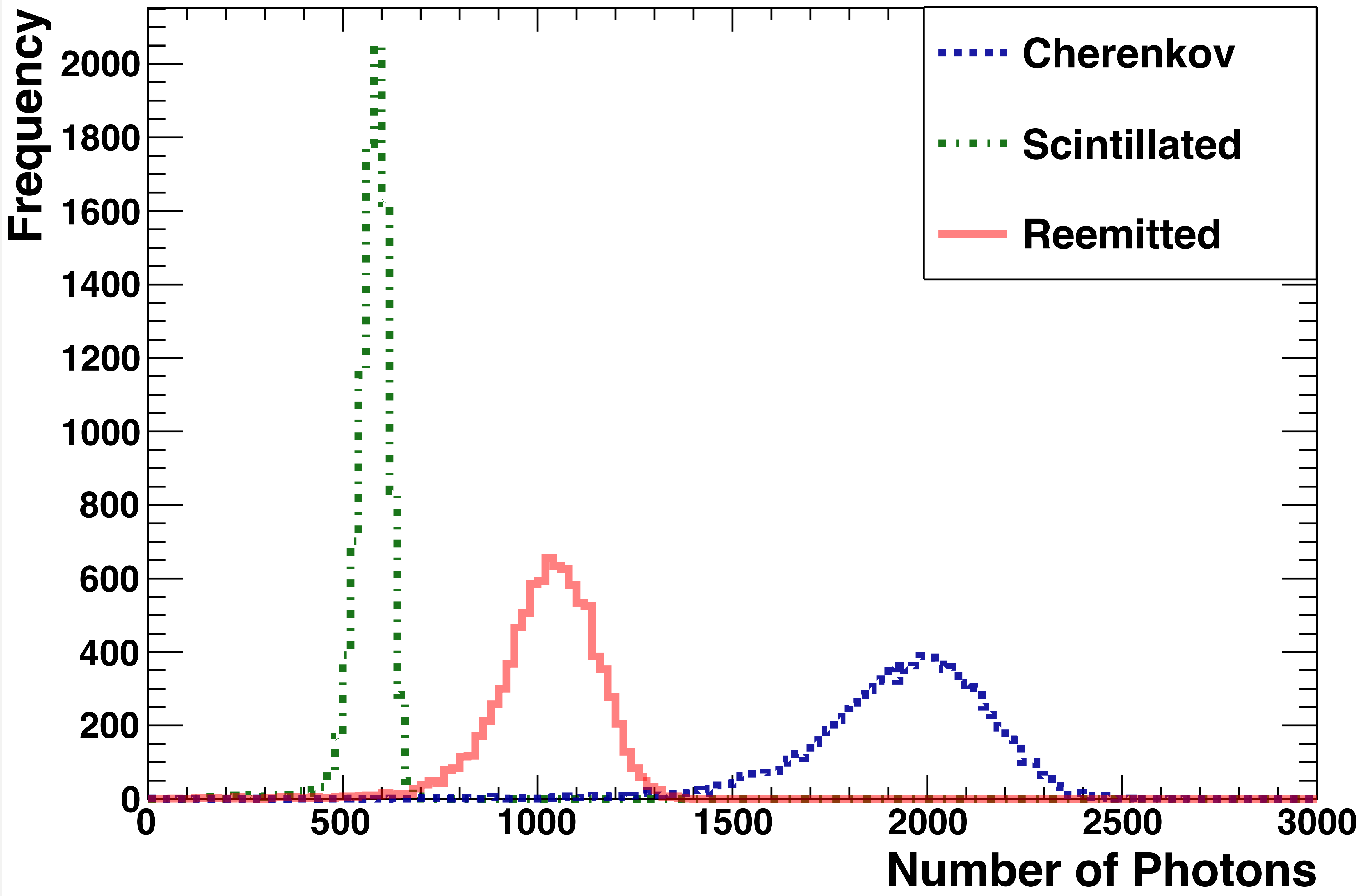
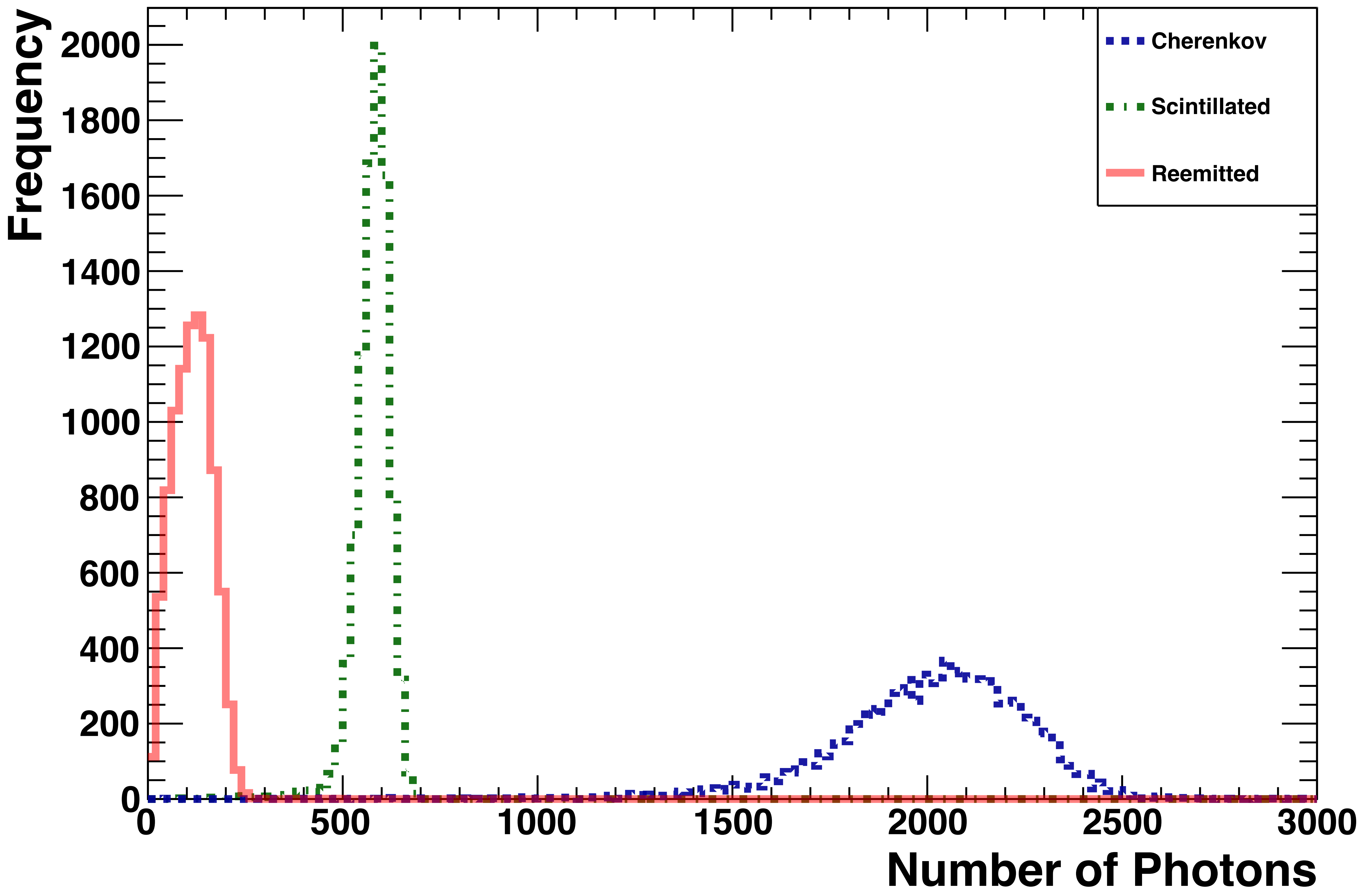
WbLS in BUTTON

Default



SAMD



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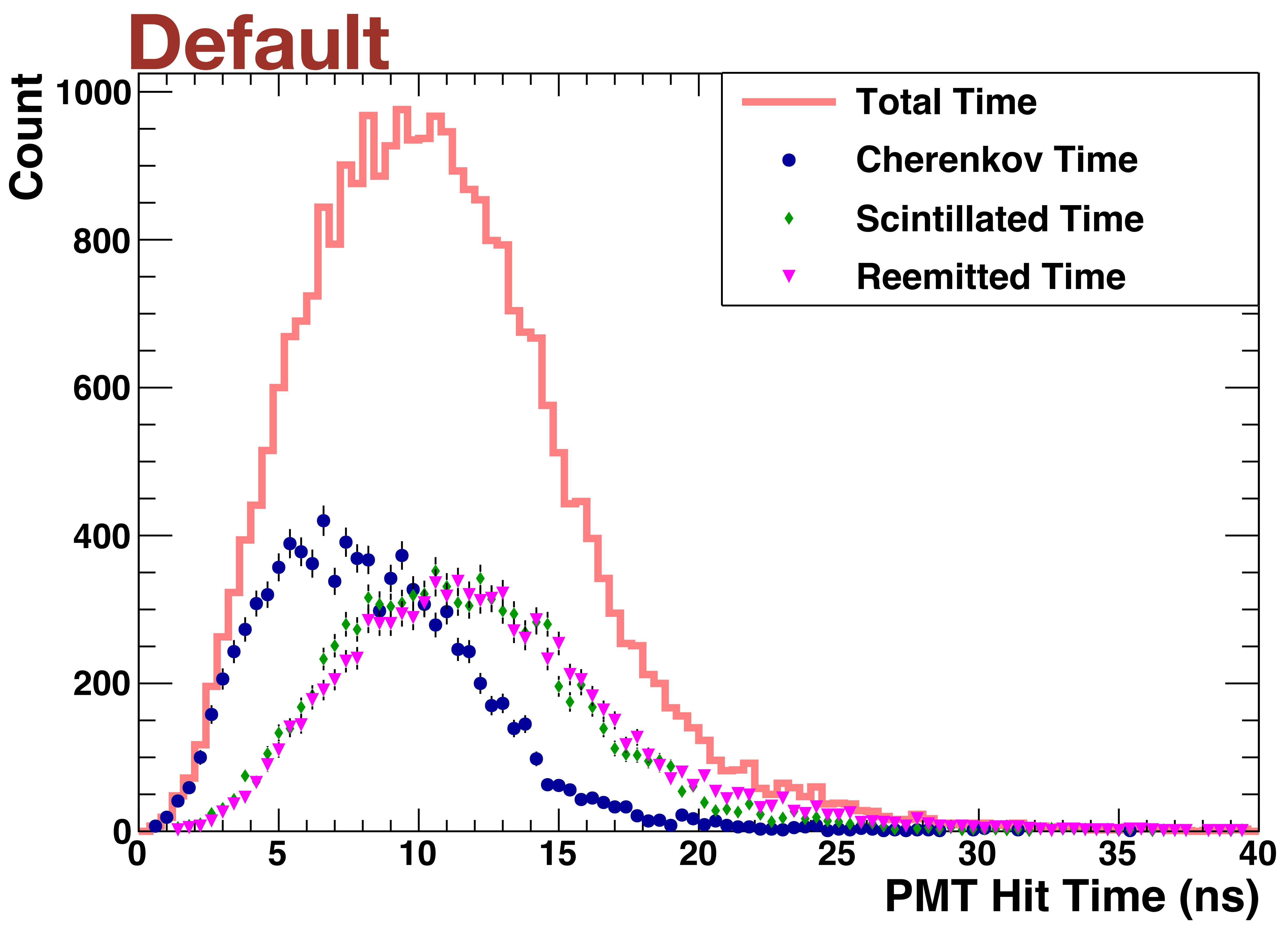
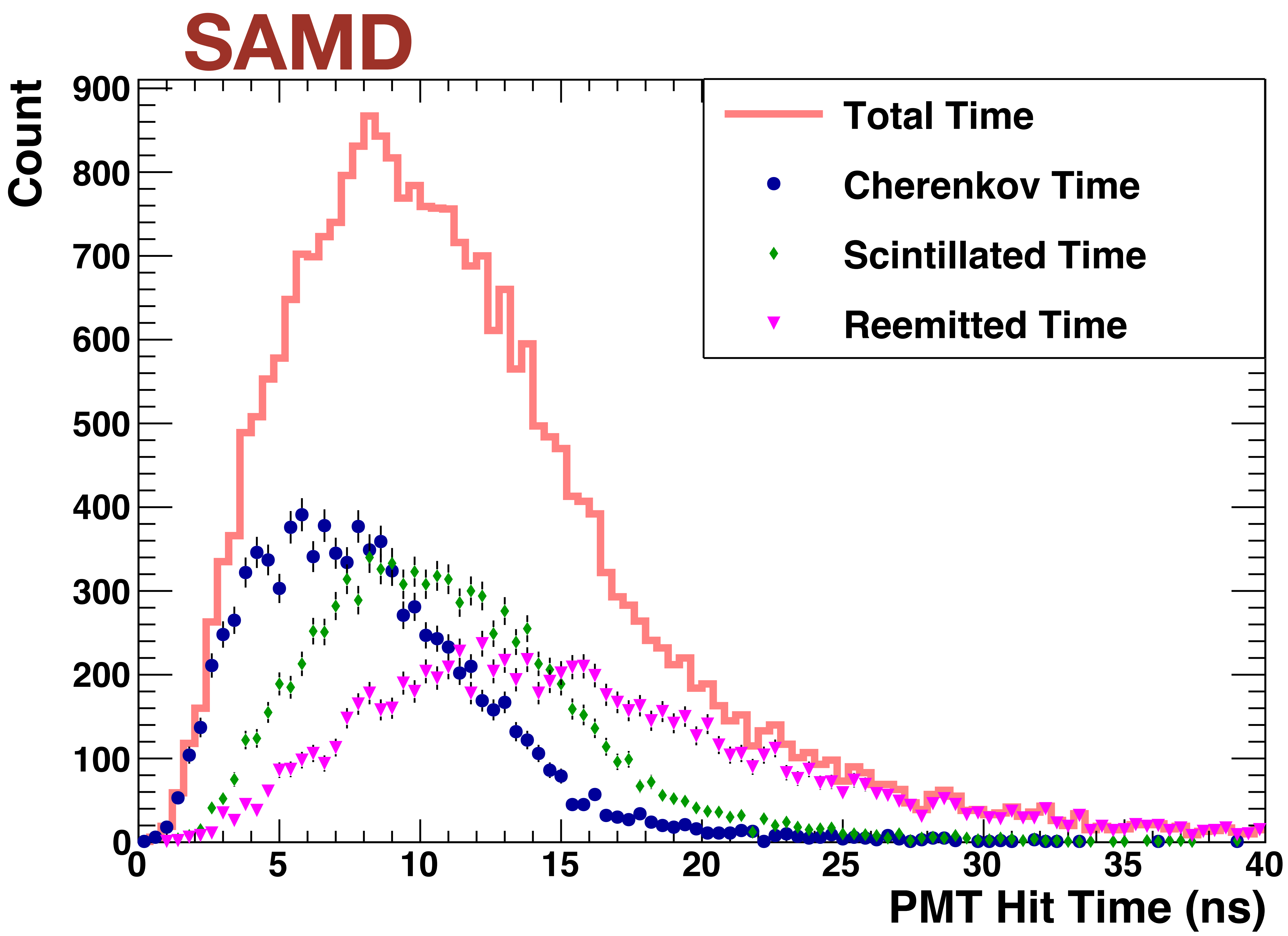
Time WbLS



Default
Count
PMT Hit Time (ns)
Total Time
Cherenkov Time
Scintillated Time
Reemitted Time



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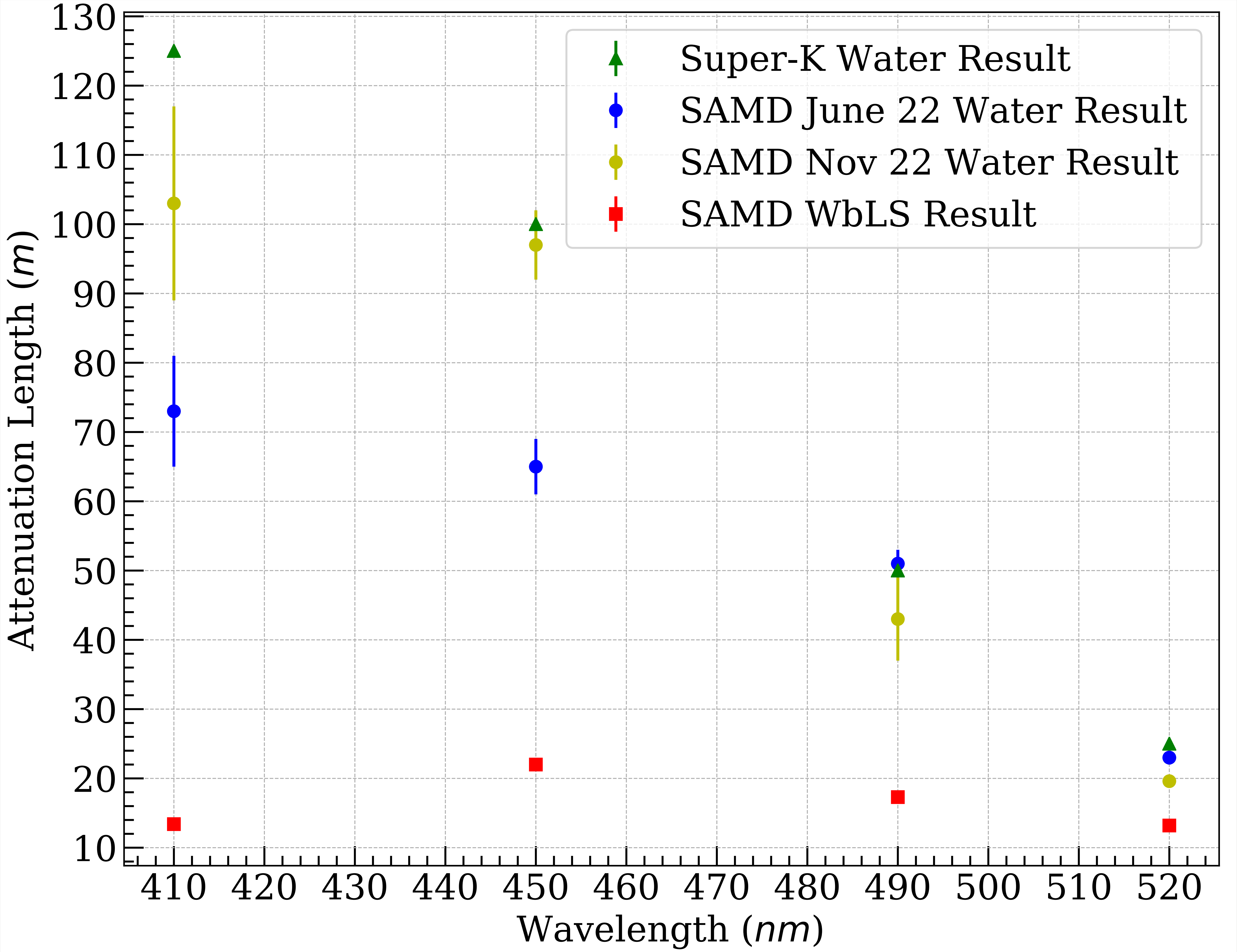
Attenuation Coefficient

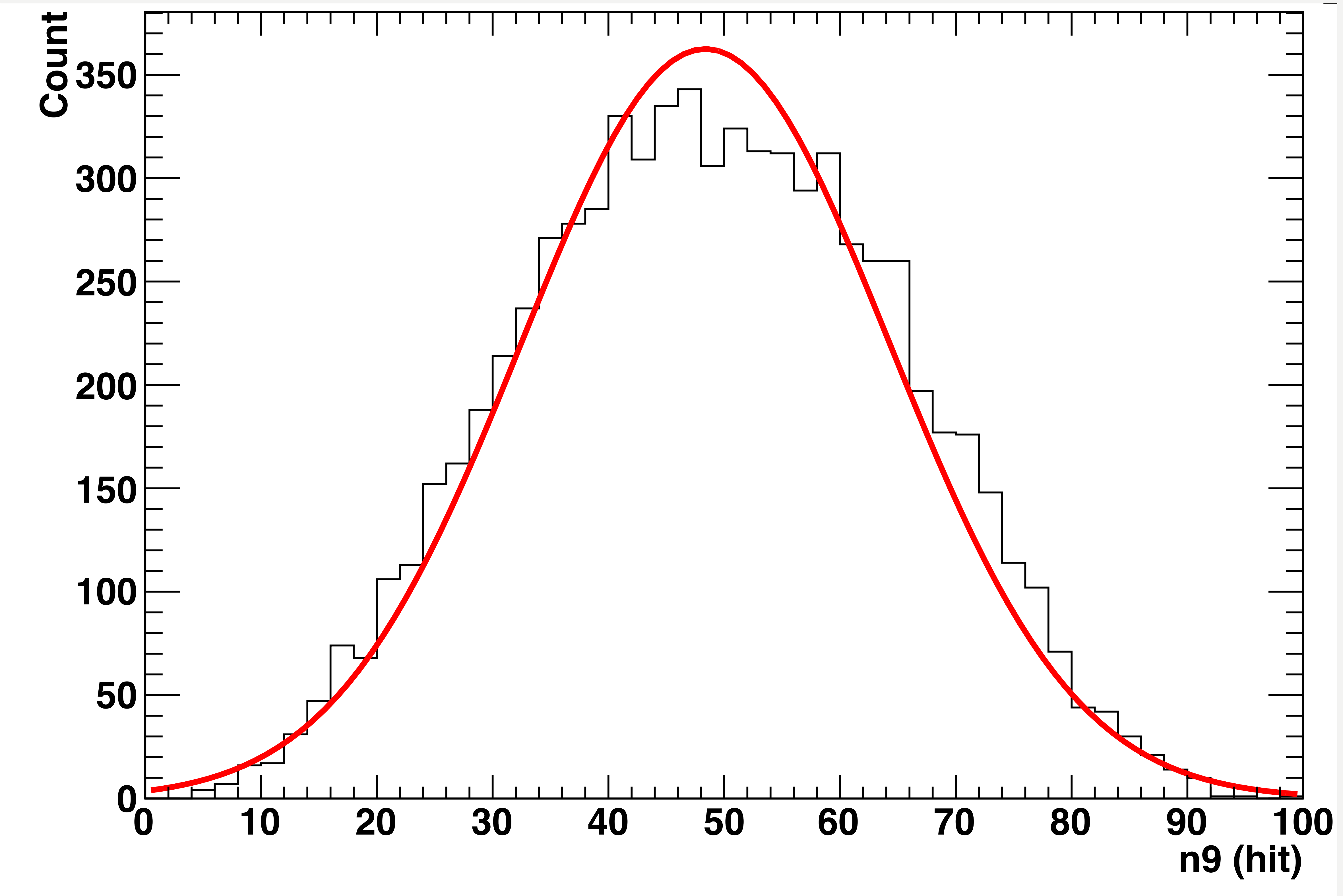


- Current WbLS fill is an addition of Water + LABPPO data
- It is not expected that these add linearly
- Can try making a new fill adding the Attenuation measurement made at Davis
- See what affect this has…

Energy, Hits and Charge

Energy and n9

- As energy increase the number of hit increase up to a saturation in hits
- Taking gaussians of electrons of monogenetic energy allow for energy and n9 to be compared
- Energy and n9 is related by $\overline{n9} = mE_{mc} + c + a\sqrt{E_{mc}}$
- Energy resolution is given by the standard deviation divided by the mean n9



- A 100 mm cut in x, y, z is made to remove events
- $\tilde{\chi}^2$= 3.98

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Energy and n9

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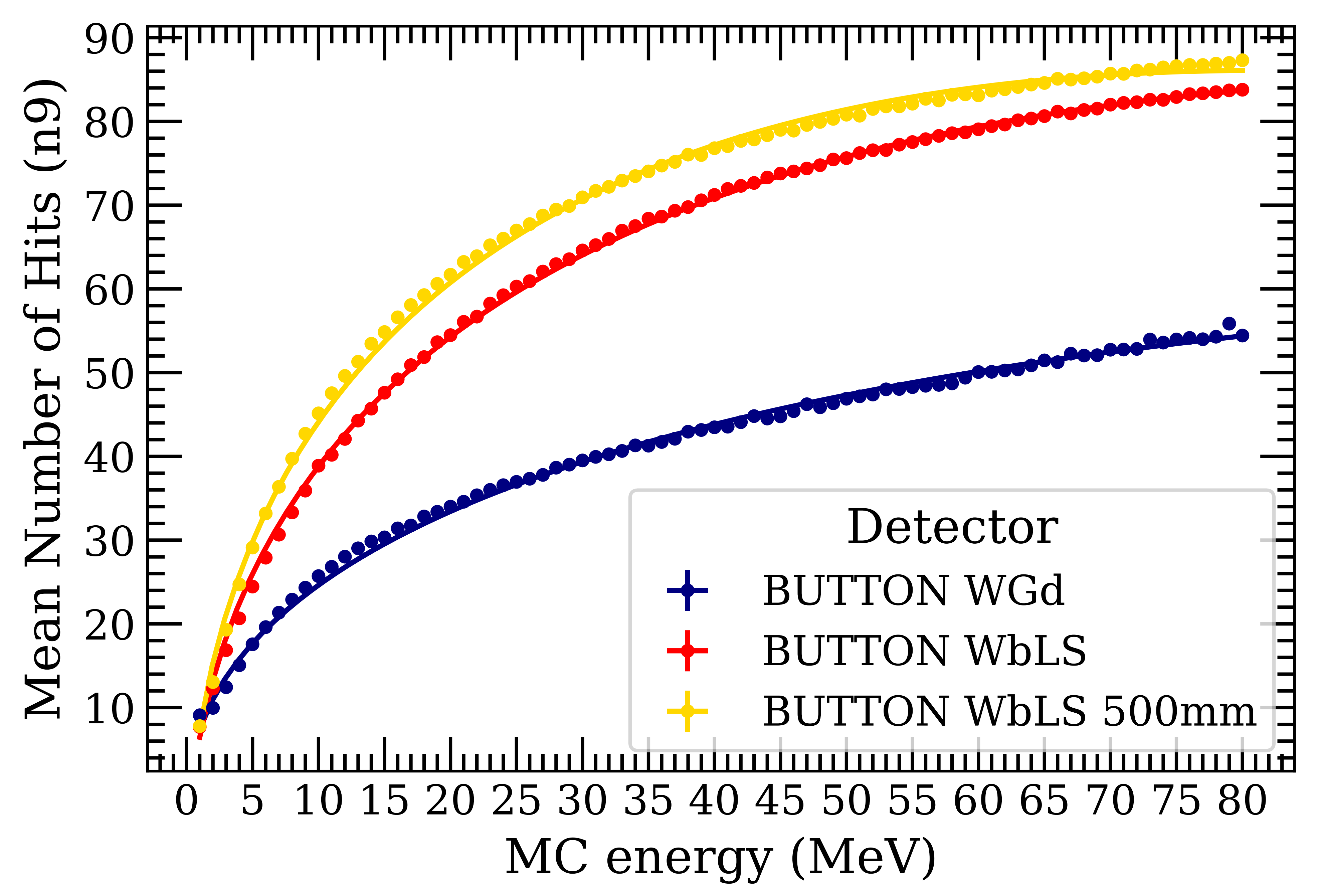

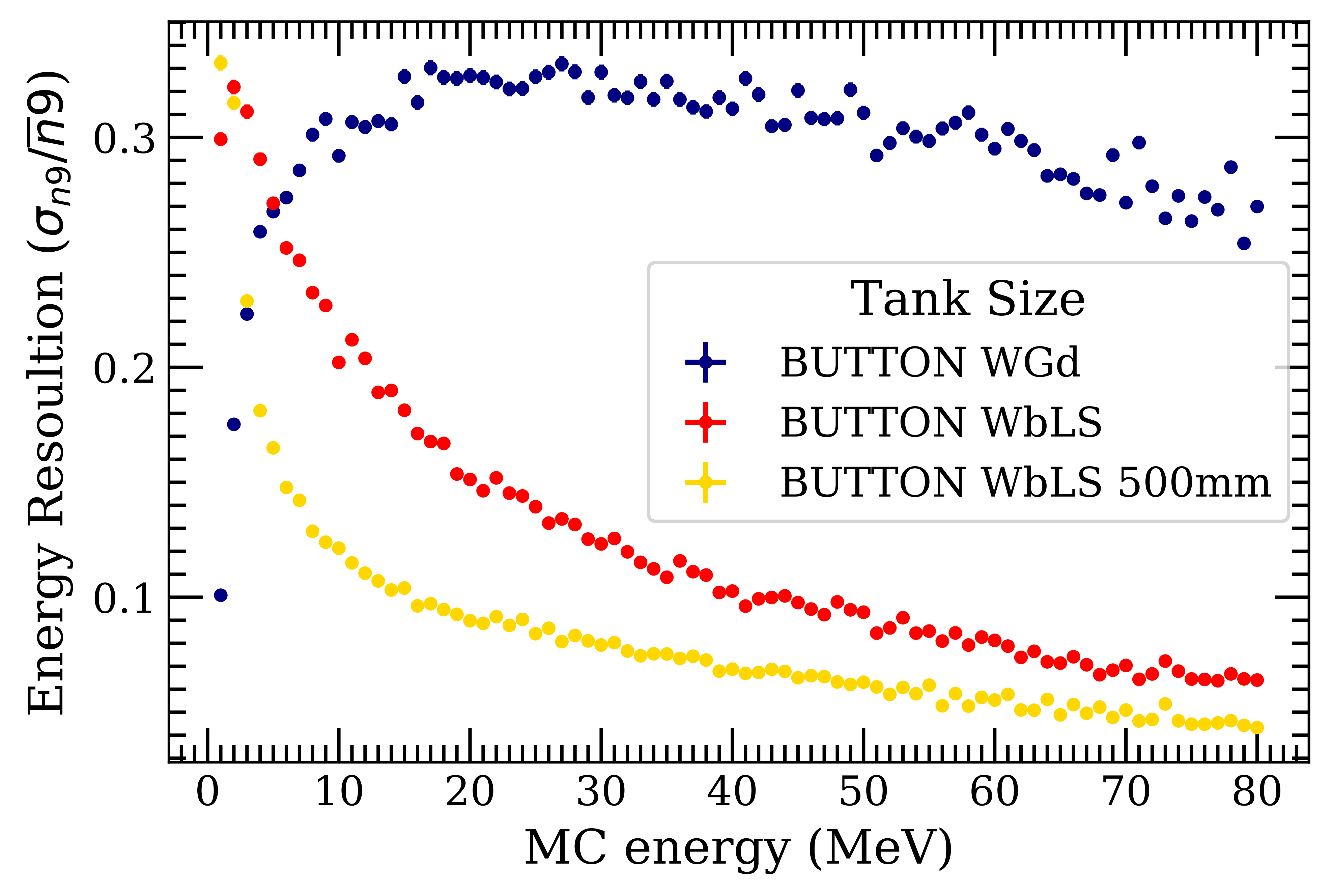

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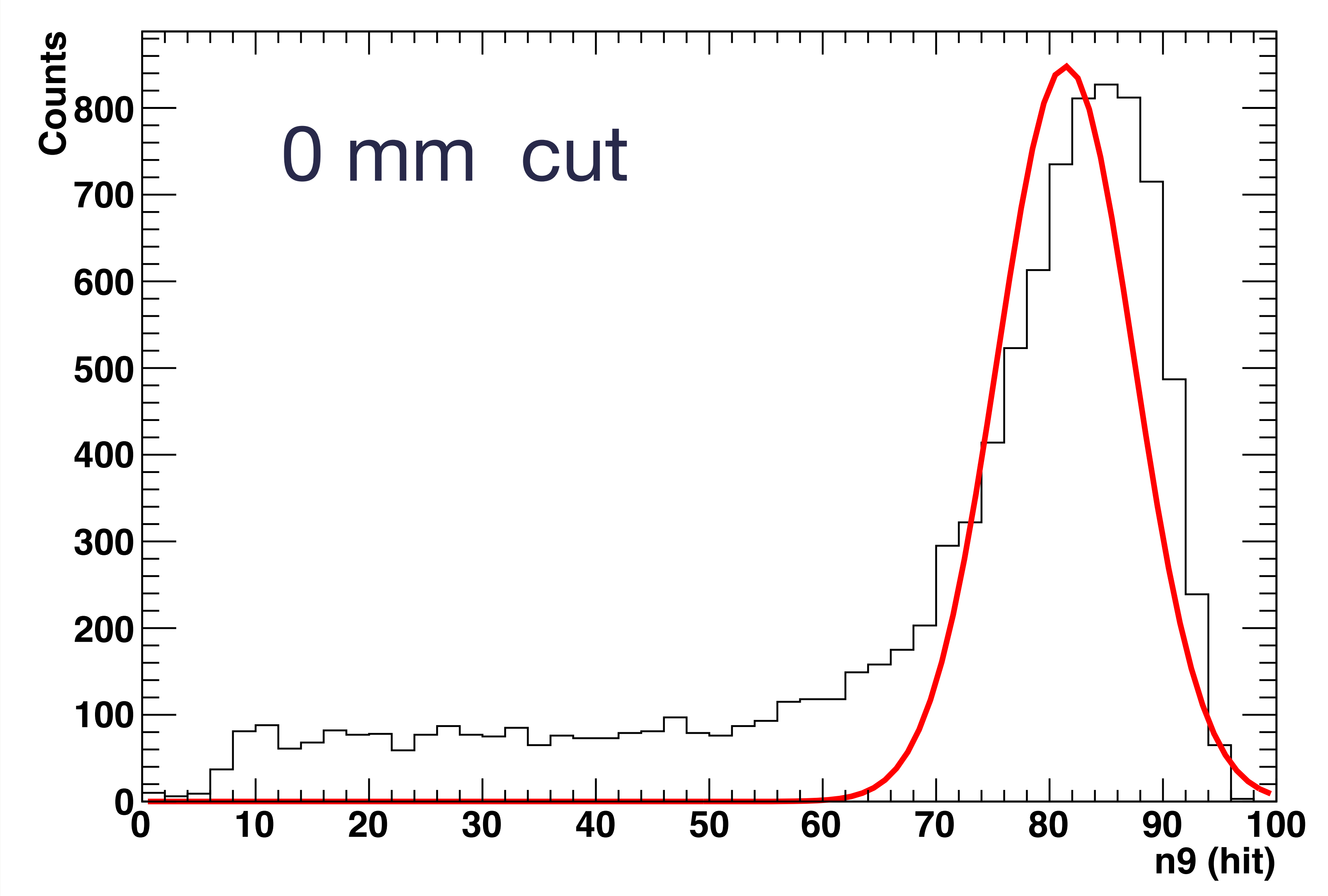
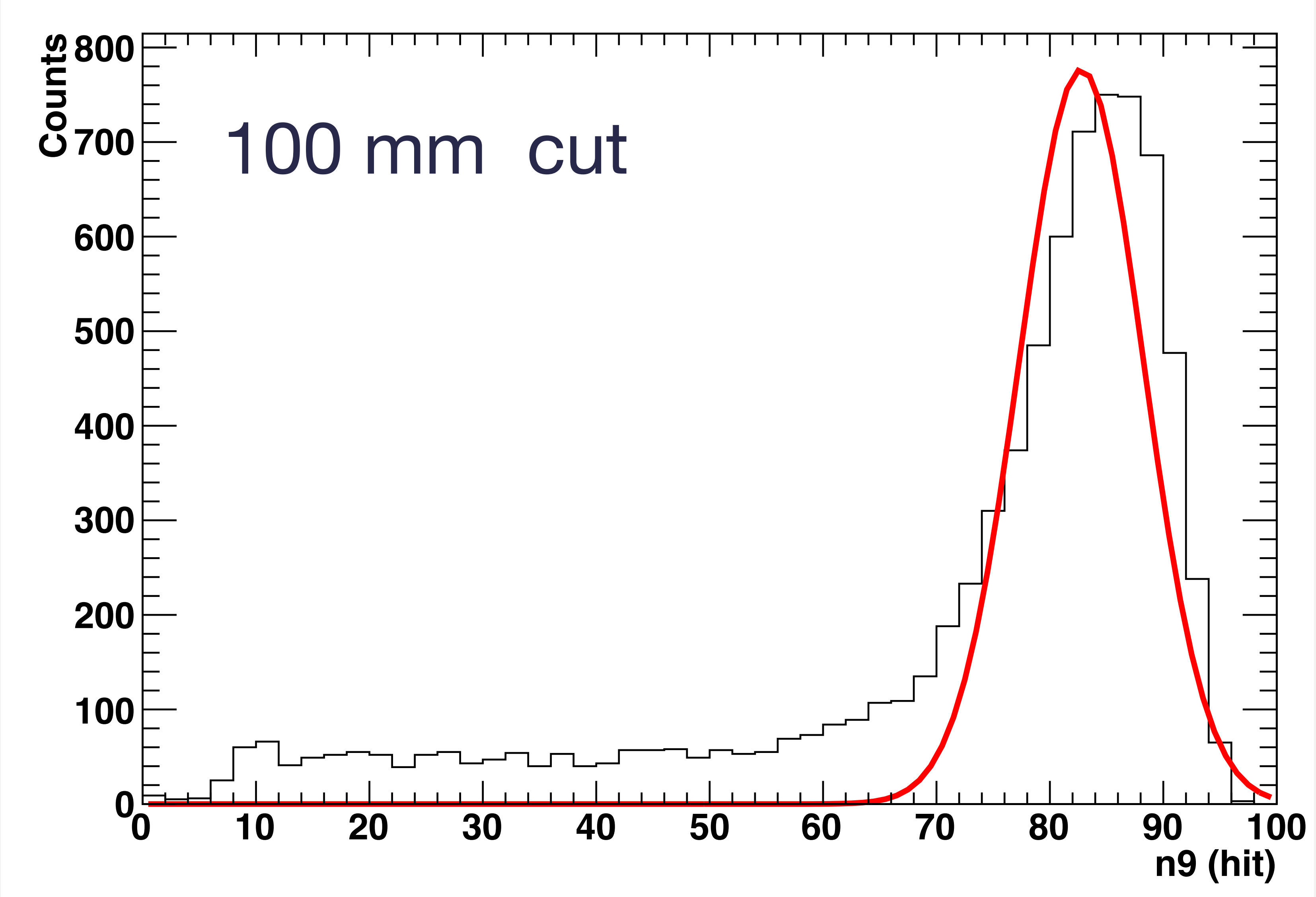
n9 cut

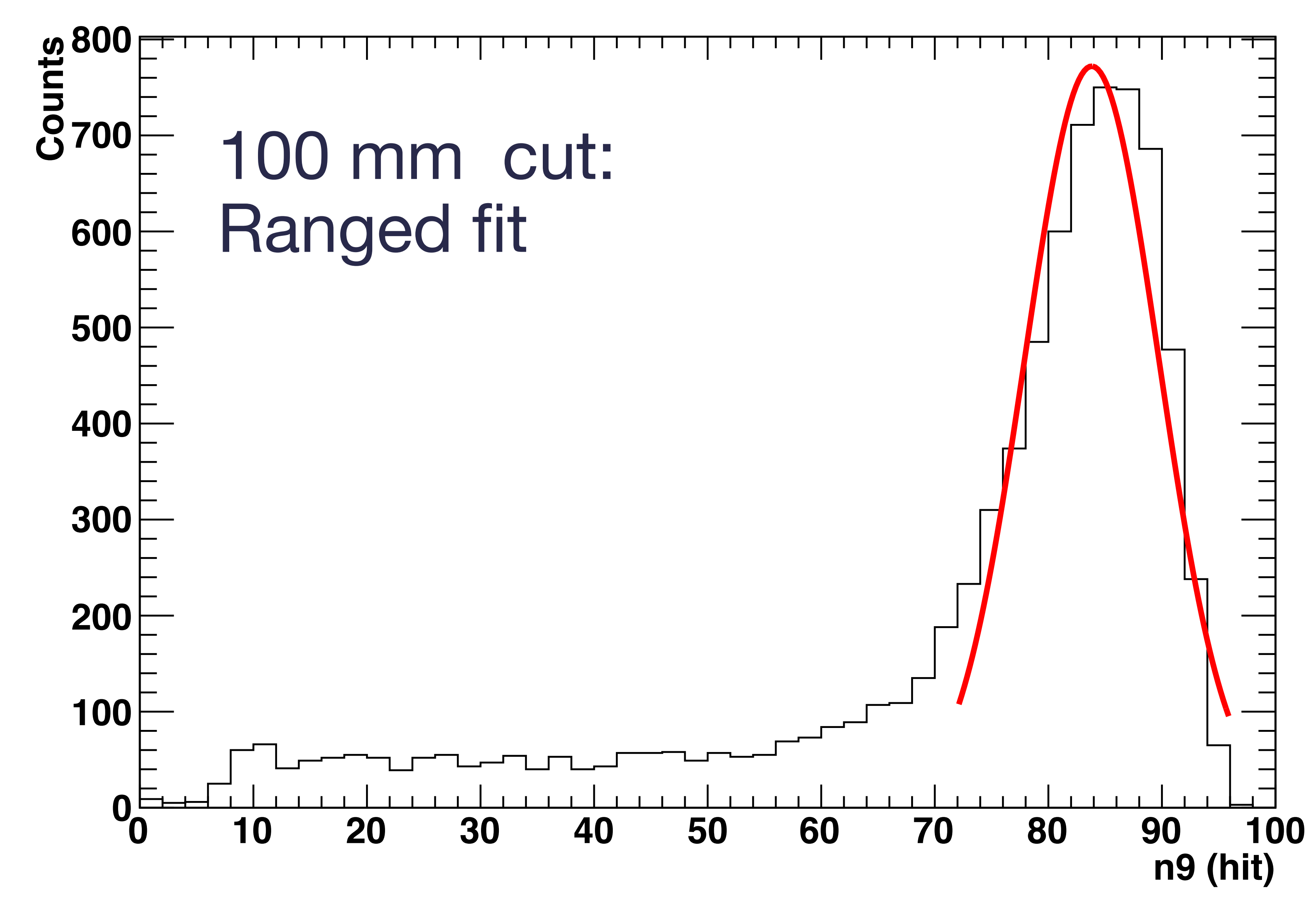
WbLS tail

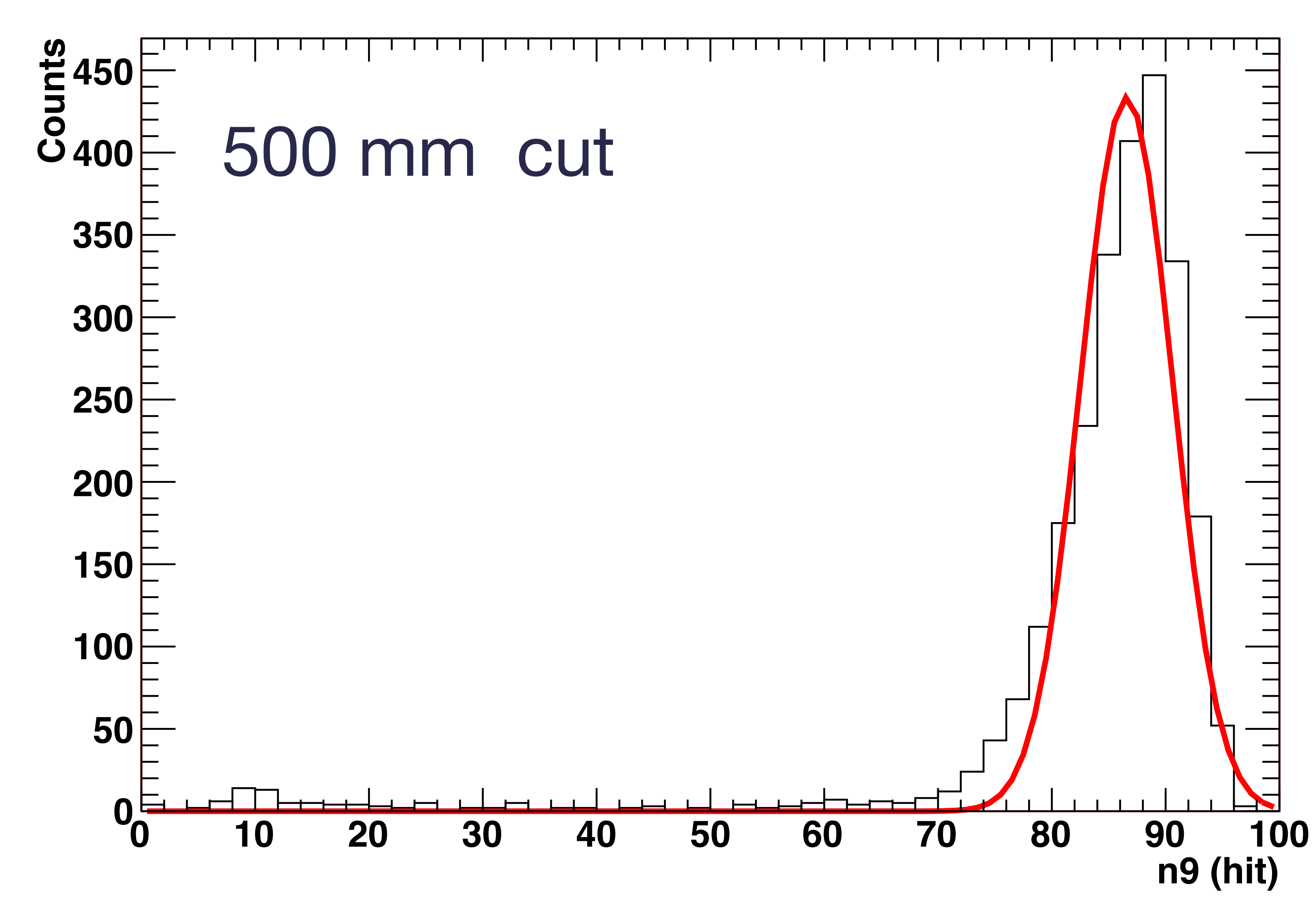
- Tail was seen in in WbLS tail

- Different cut were used to find the reconstructed distance required to remove tail



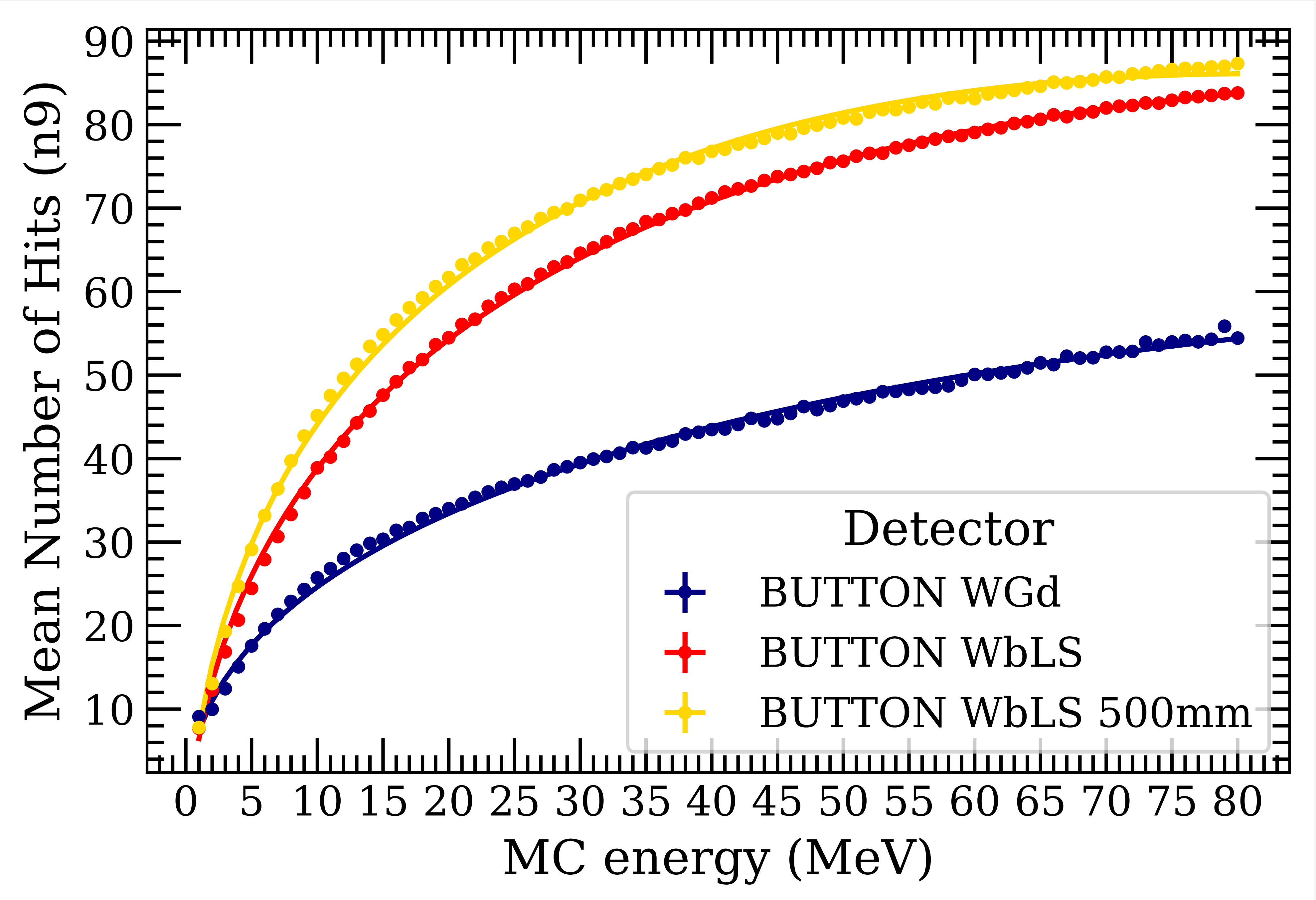


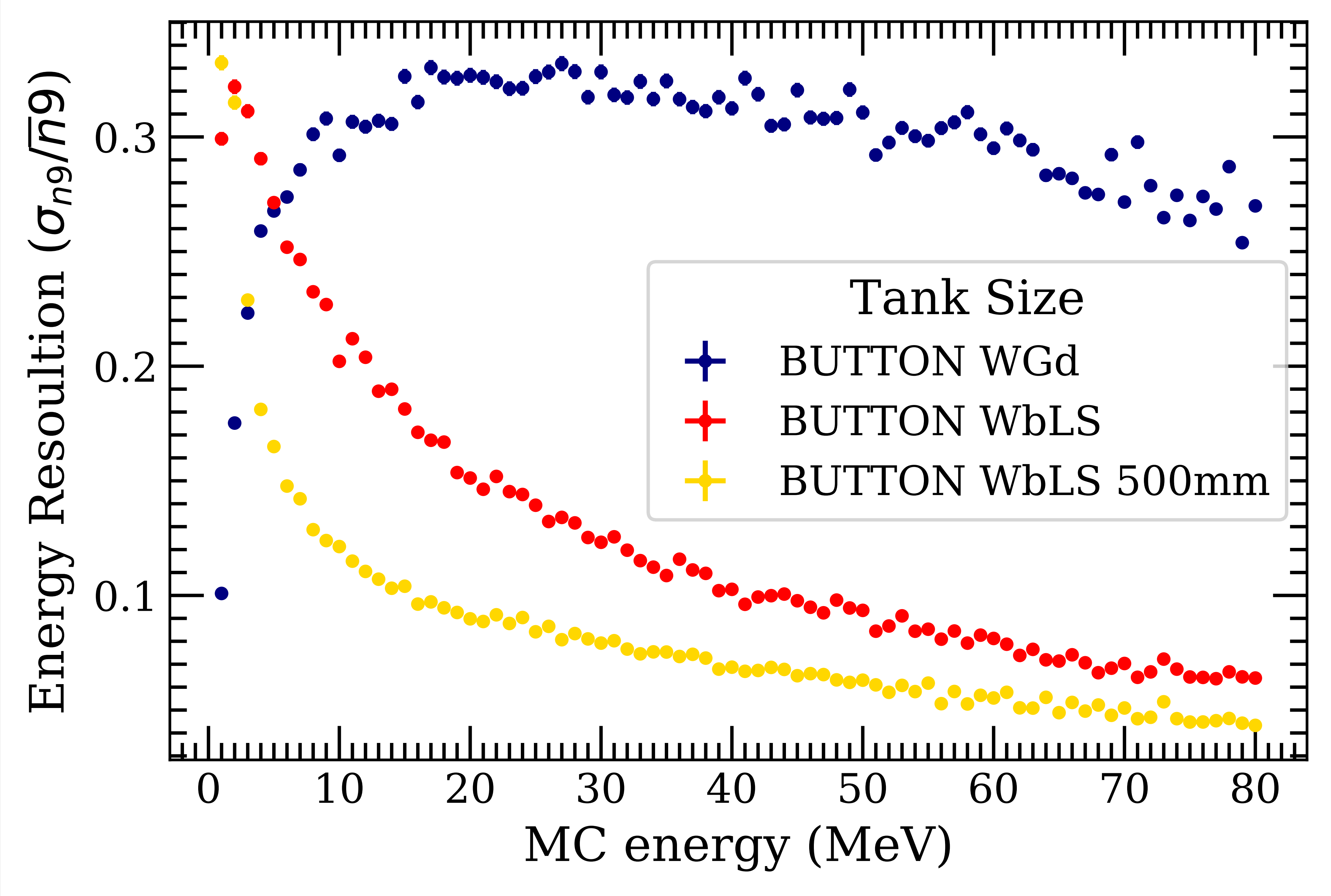




Energy and n9

- As energy increase the number of hit increase up to a saturation in hits.
- Taking gaussians of electrons of monogenetic energy allow for energy and n9 to be compared
- Energy and n9 is related by
  $\overline{n9} = mE_{mc} + c + a\sqrt{E_{mc}}$
- Energy resolution is given by the standard deviation divided by the mean n9
- Charge and hit windows optimised (see backup)



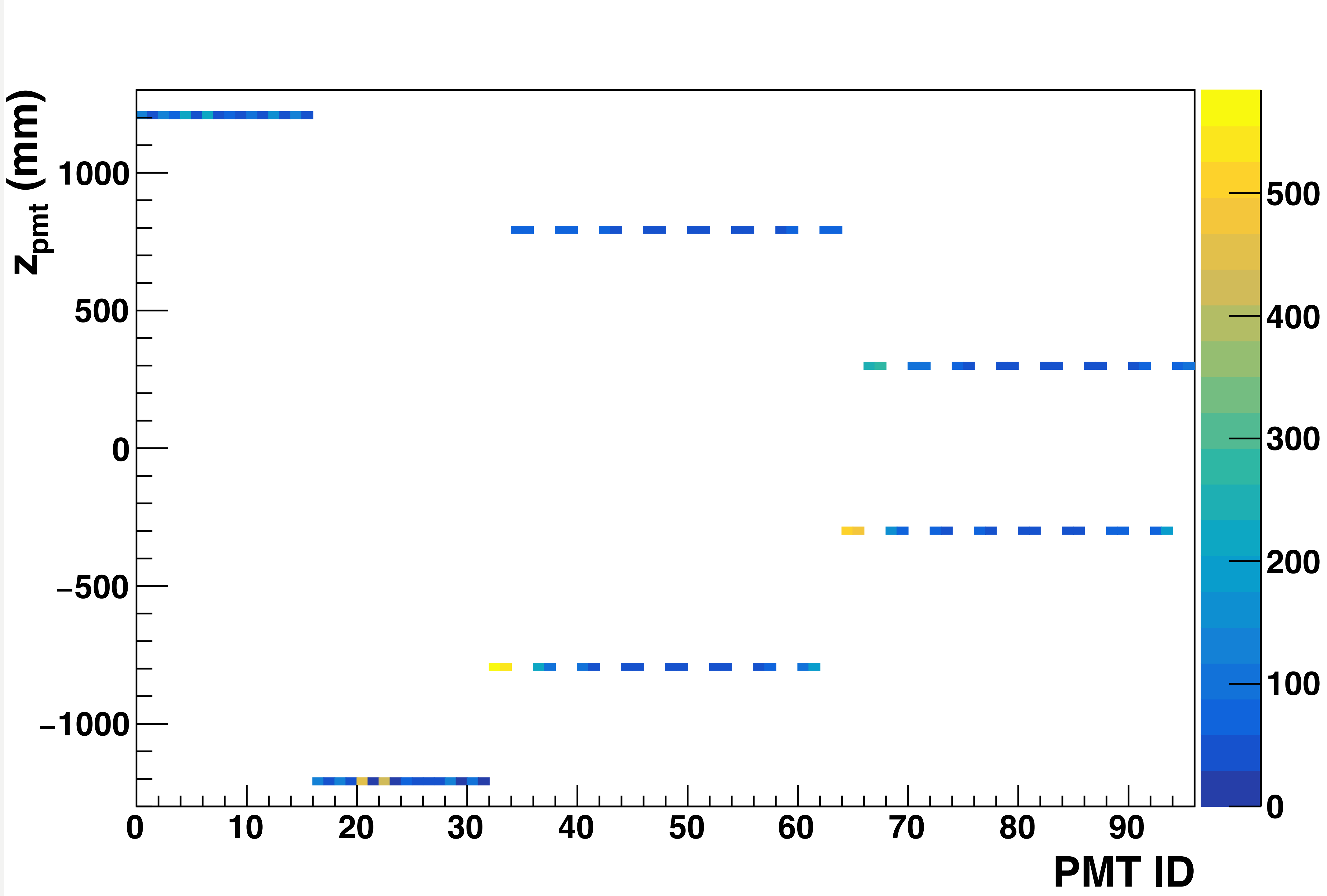


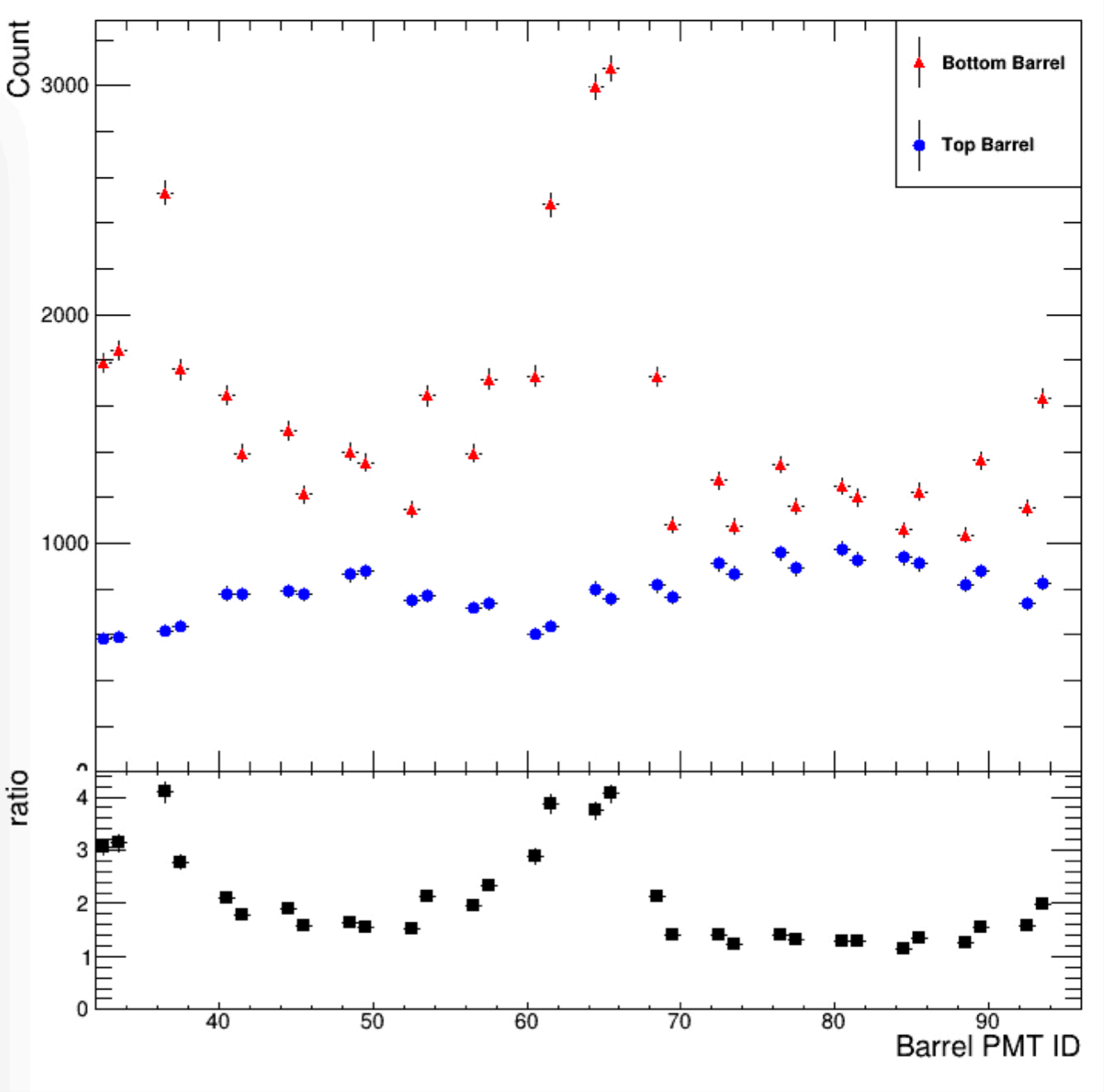
Vertex Resolution

Diffuser Cone

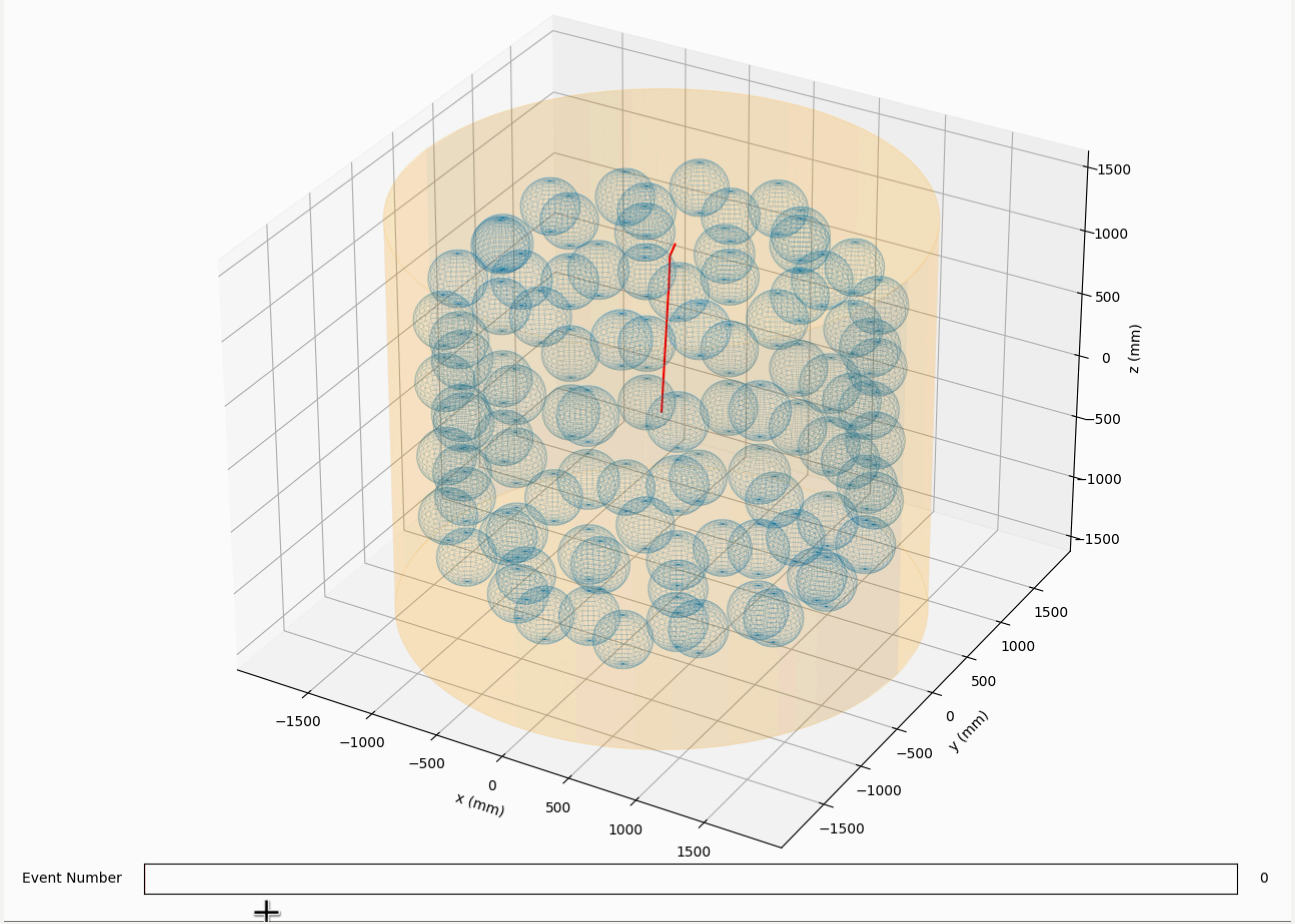
Diffuser Pointing

- Positioning the diffuser on middle horizontal frame
- Expect to see even distribution of hits in the barrel
- Next step: develop a event viewer to see events





Monte Carlo Event Viewer



- Use track information to see the track from fired photons
- See photons are fired up
- Translating θ and ϕ to the horizontal position is the next step

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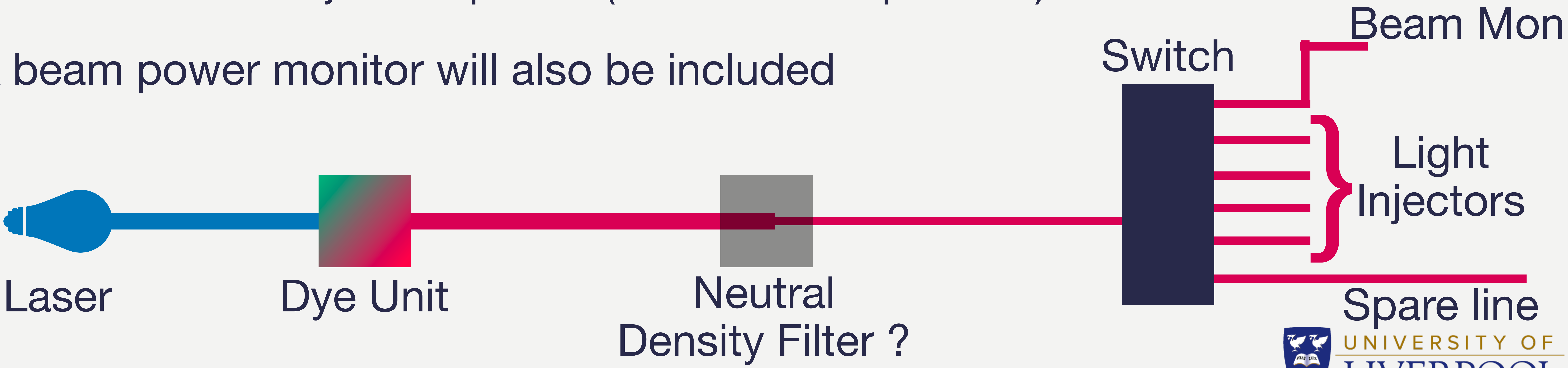
Diffusor

Light injection

The What, Where and Why

- SK like diffusors will be installed on Button for performance and calibration purpose
- This will use a 337.1nm laser (Dye unit used to change wavelength) with a 3ns pulse width (might be to broad)
- Plan too have 4 injection points (where is the question)
- A beam power monitor will also be included



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Spherical coordinates

Getting the geometry right

- The photons are fired in spherical coordinates

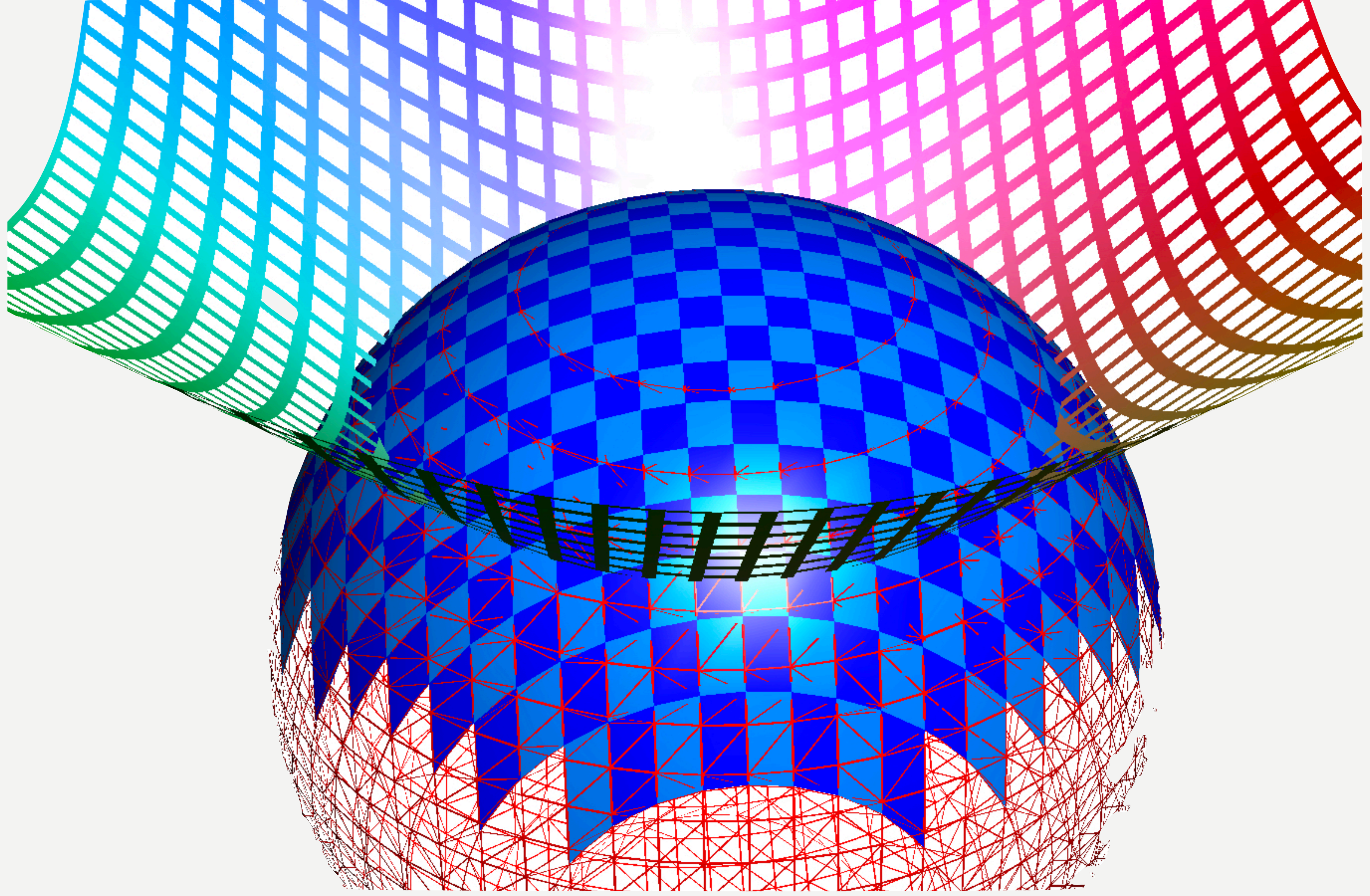
- To produce a ‘ice cream’ cone the by the following,

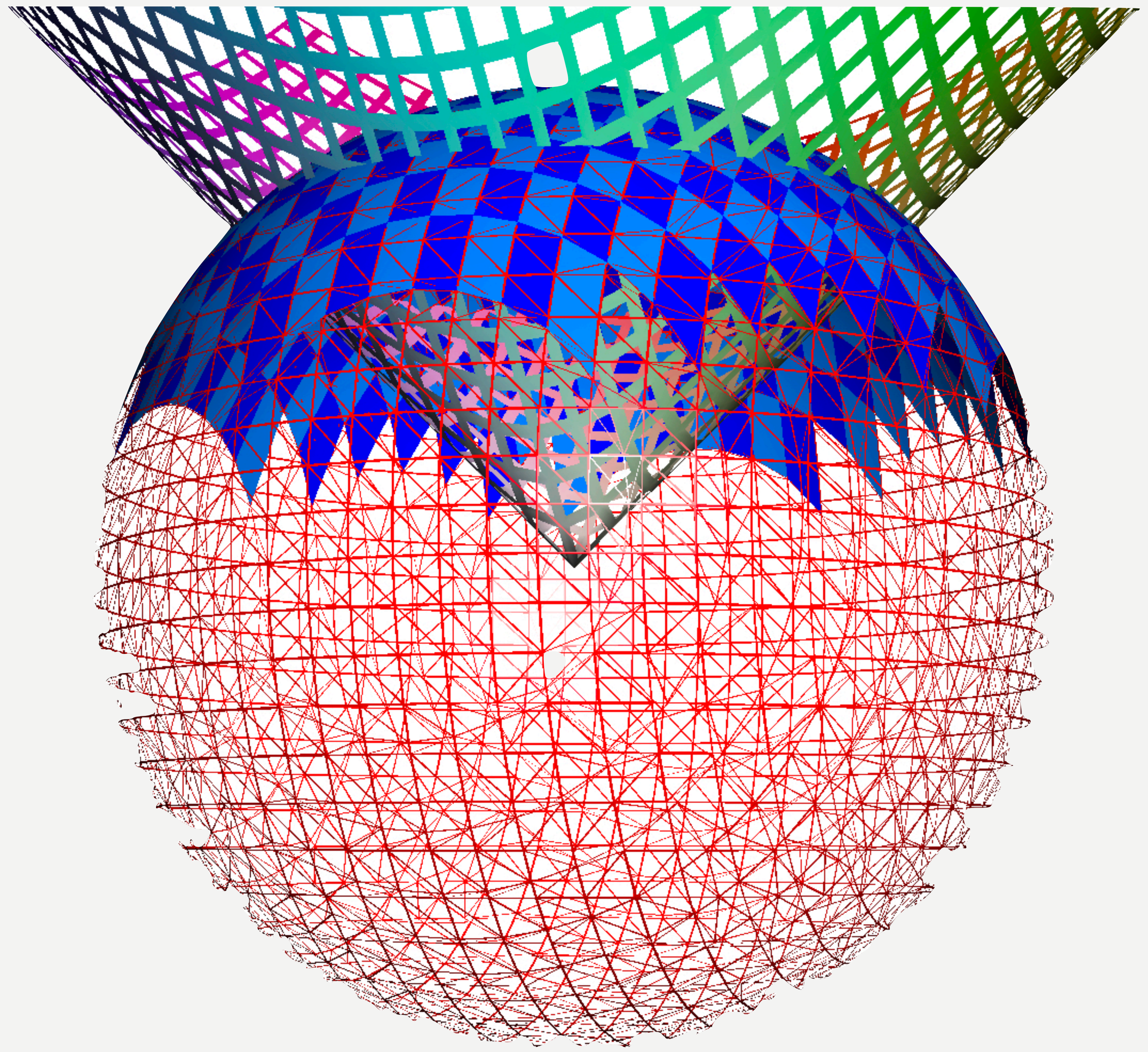
Sphere is defined as –> $$1 = z^2 + x^2 + y^2$$

HemiSphere –> $$z = \sqrt{1 + x^2 + y^2}$$

Cone –> $$z = n\sqrt{x^2 + y^2}$$

- The bound between the hemisphere and cone





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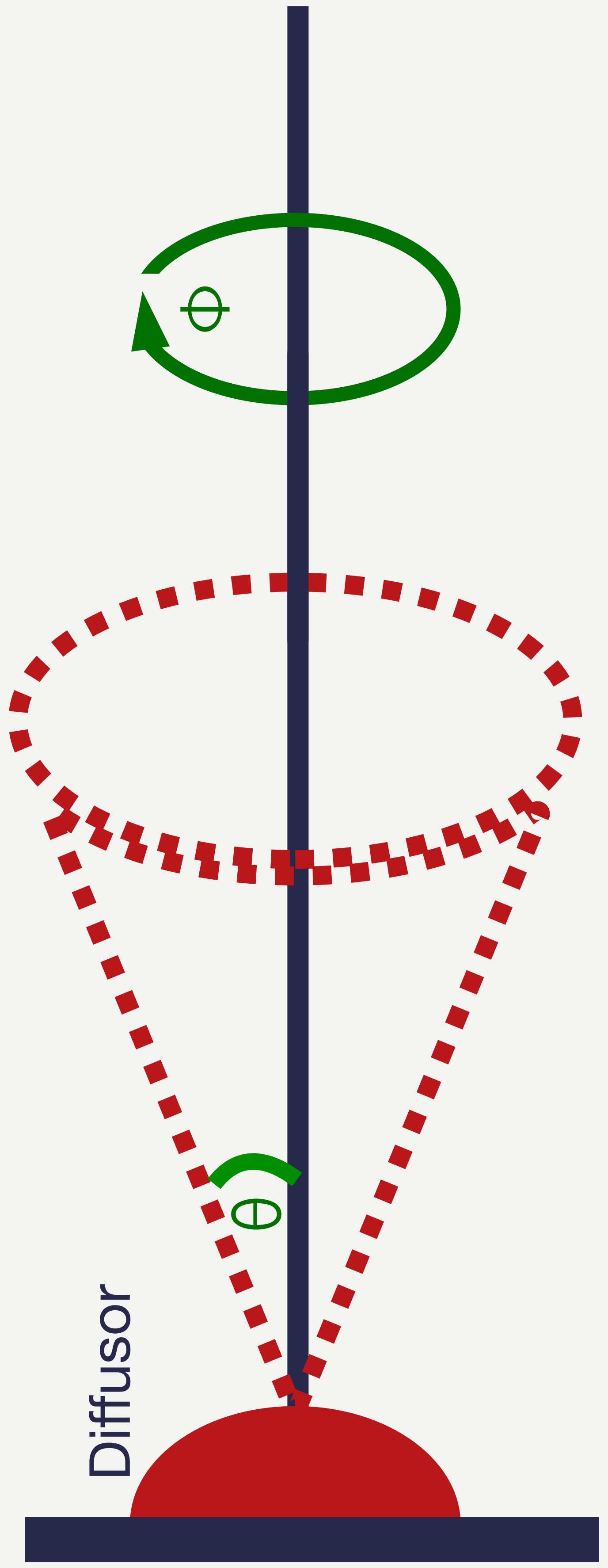
What about light cones

Translating this into θ & ϕ

- All that is known is the opening angle α
- In the simple case the cone is pointing in the positive z direction
  - ϕ is distributed between 0 to 2π
  - $\alpha = 2\theta$
  - $\cos\theta$ is uniform between -1 to 1 then only $\alpha > 2\theta$ are selected
  - r=1 (can in this case ignore r)
- This should produce a cone pointing at the top pmt



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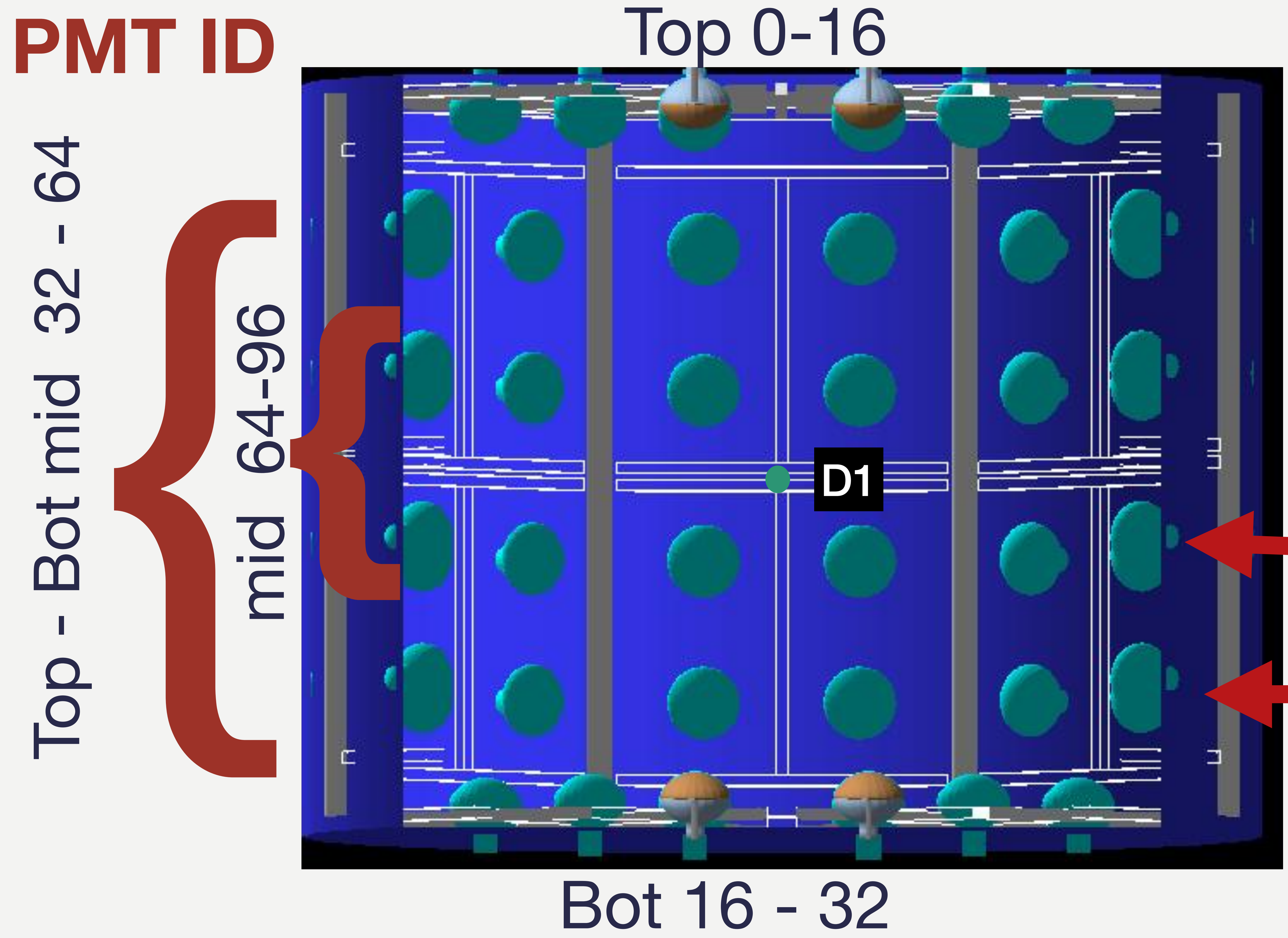
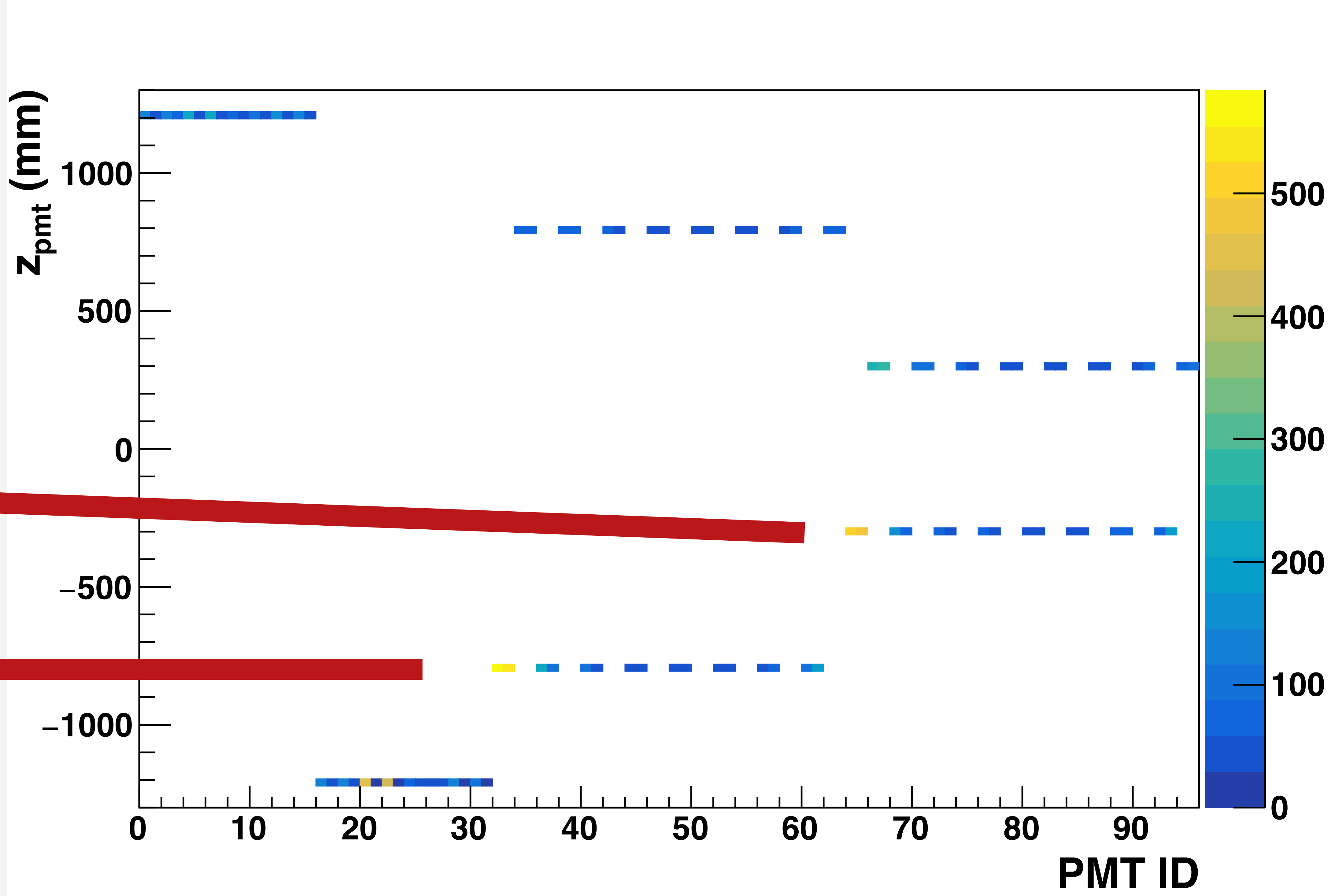
Z Position - Diffuser
Where are the PMT

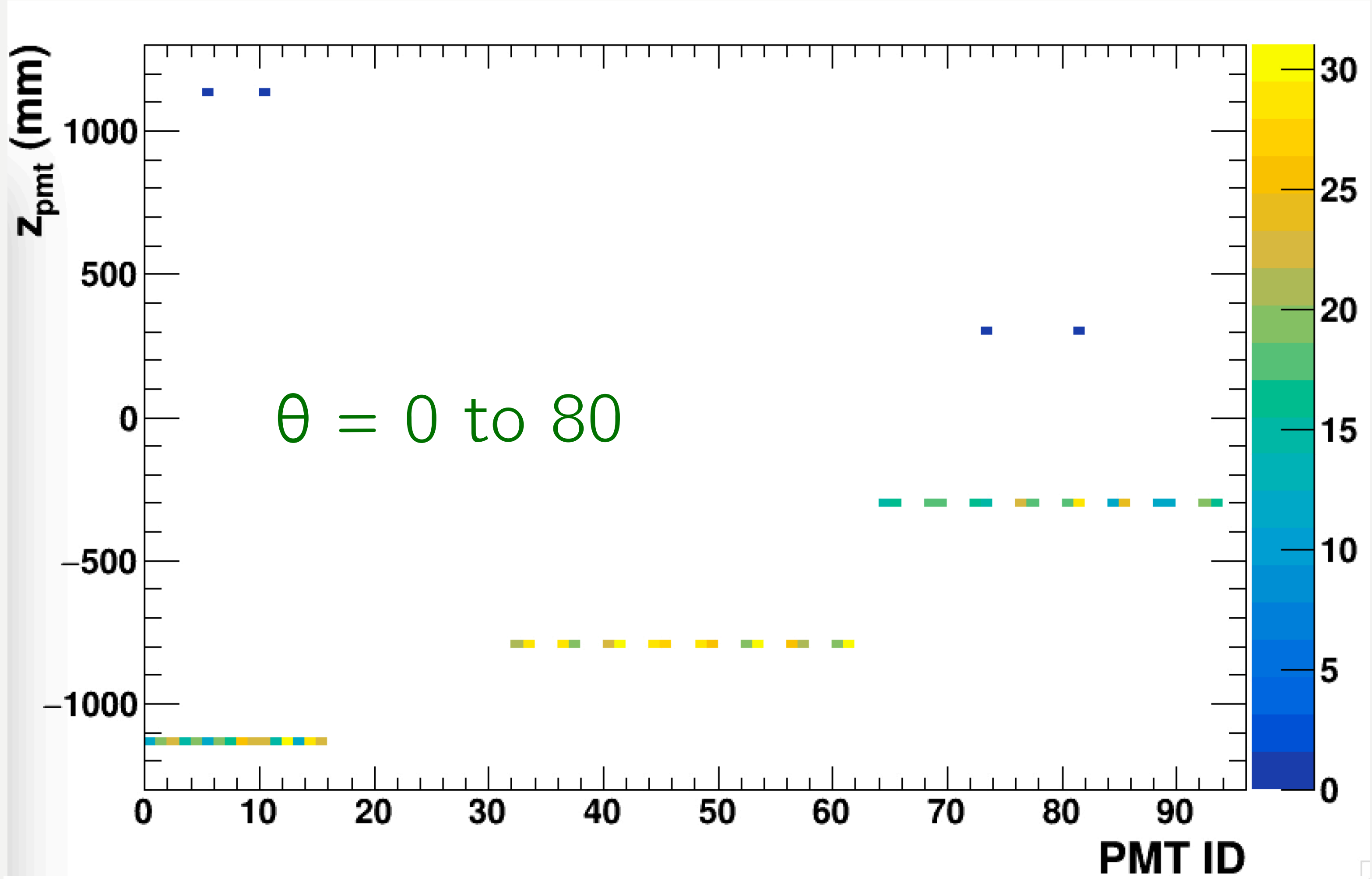
- Using the diffuser at a D1
- Hit intensity suggest that the diffusor is pointed downwards

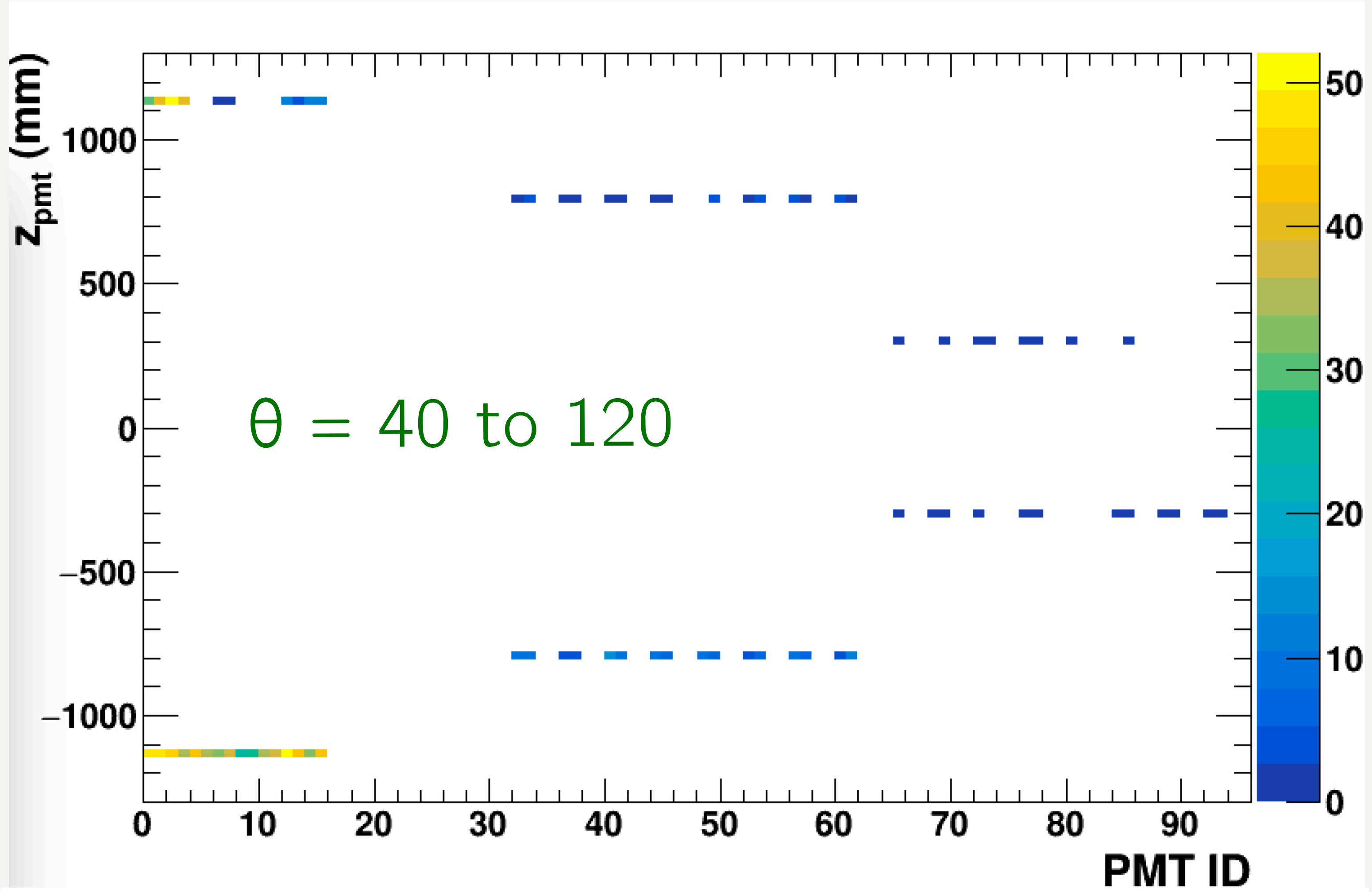


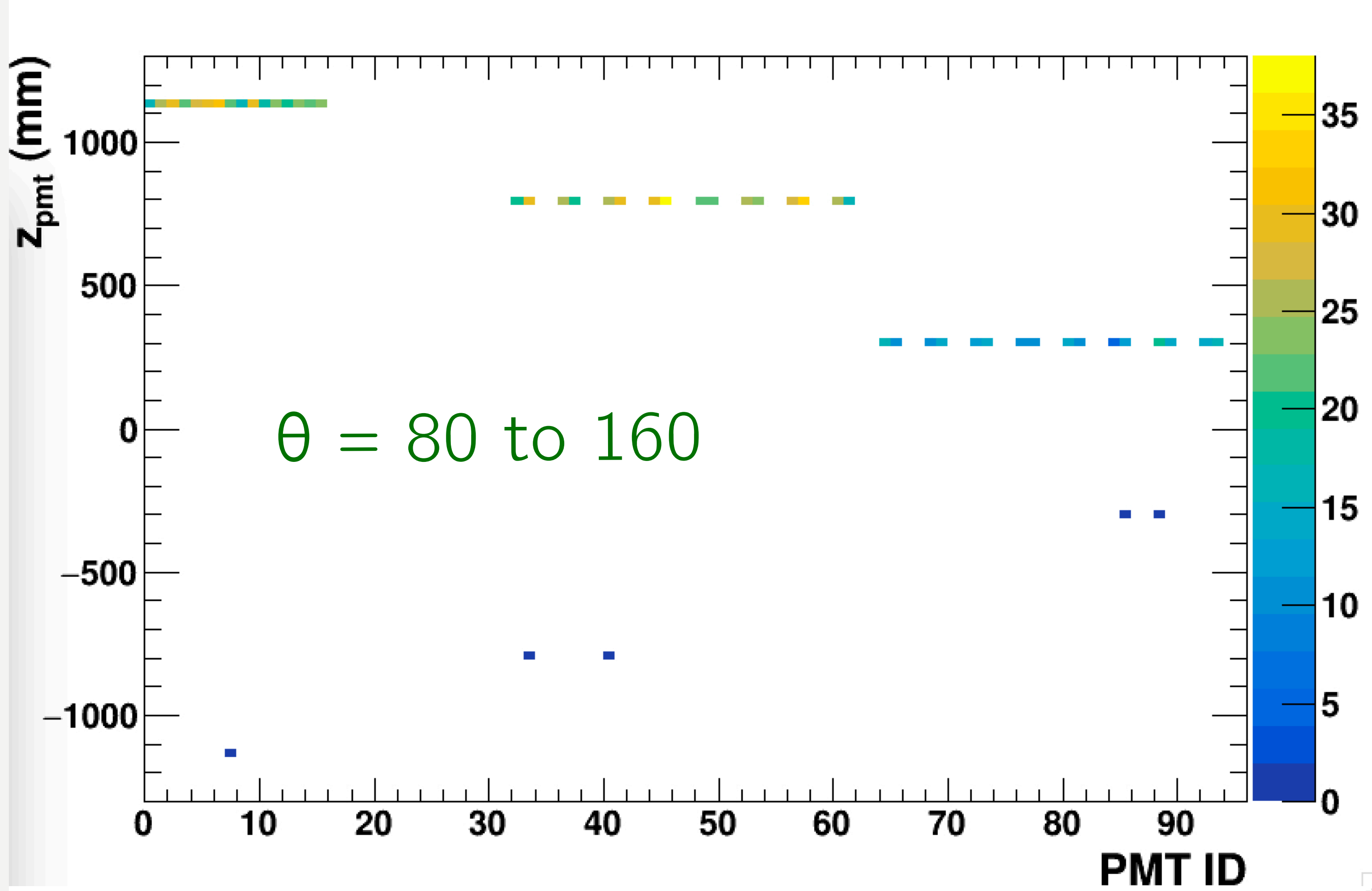


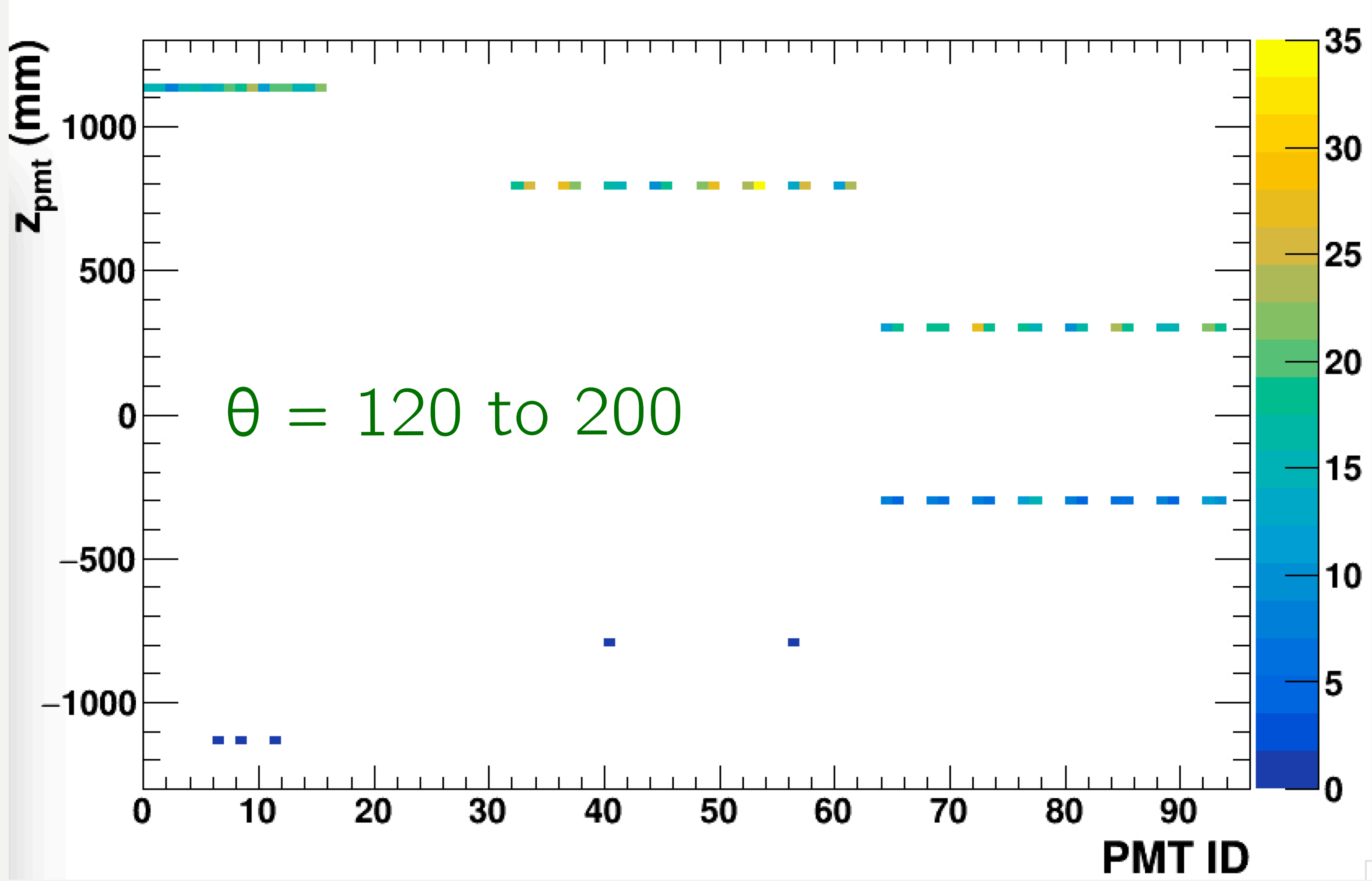
Angle and hits

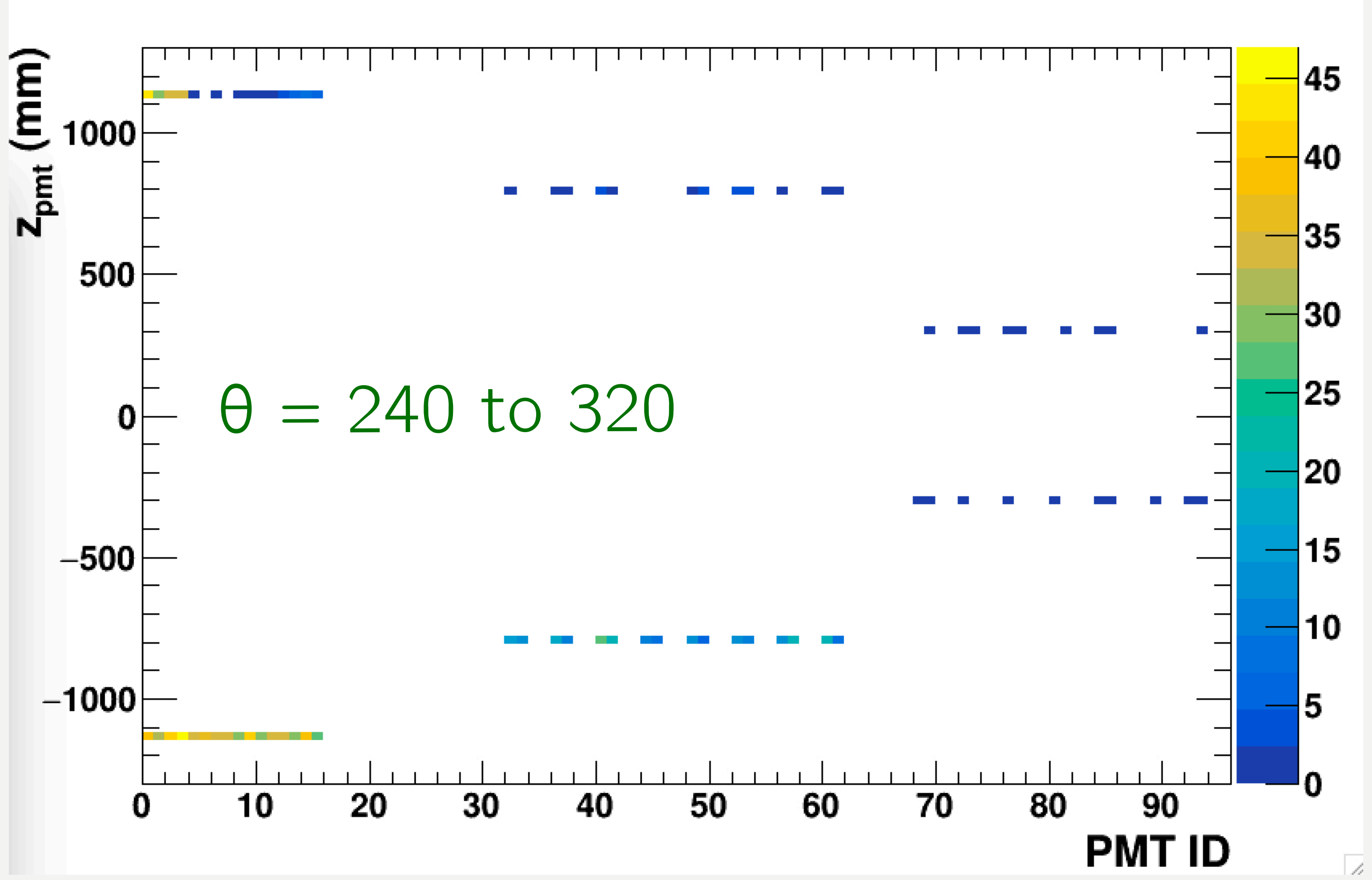
What way does my diffusor point

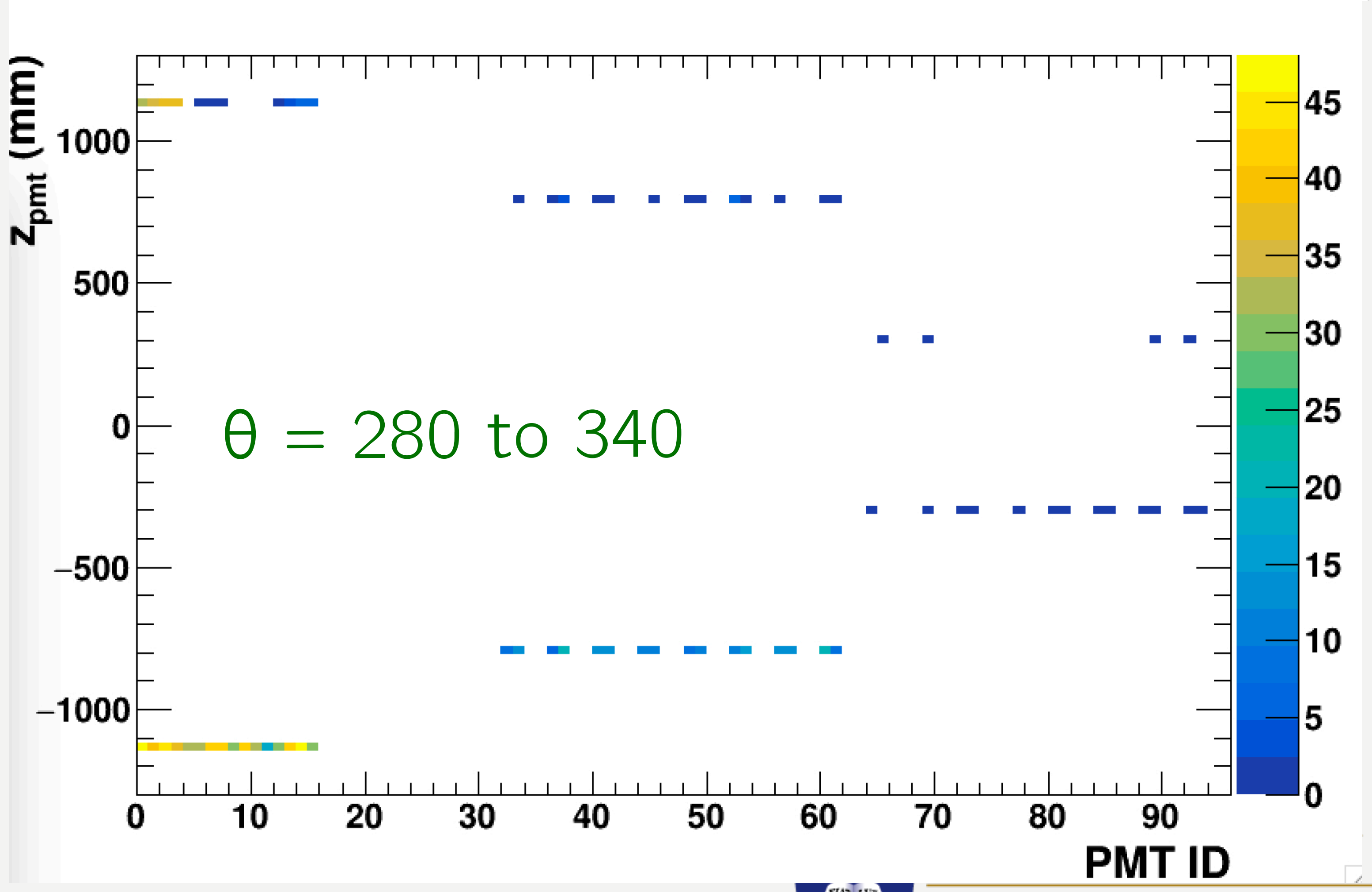






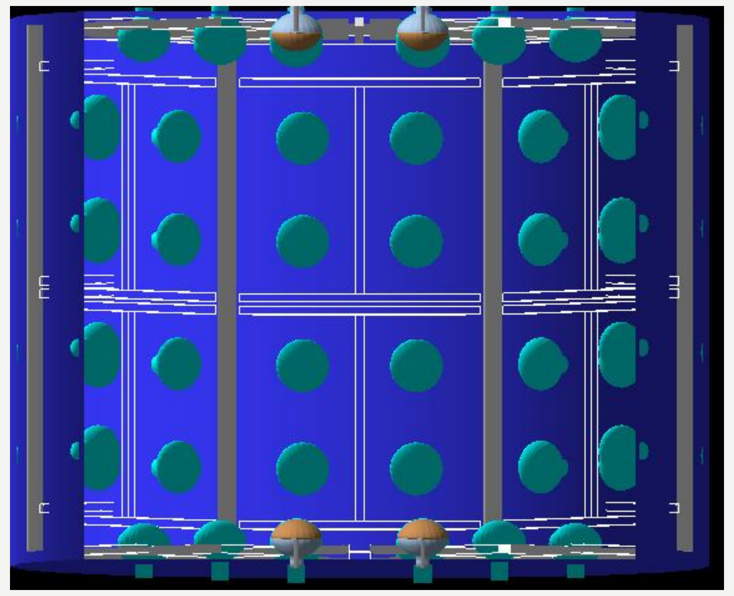


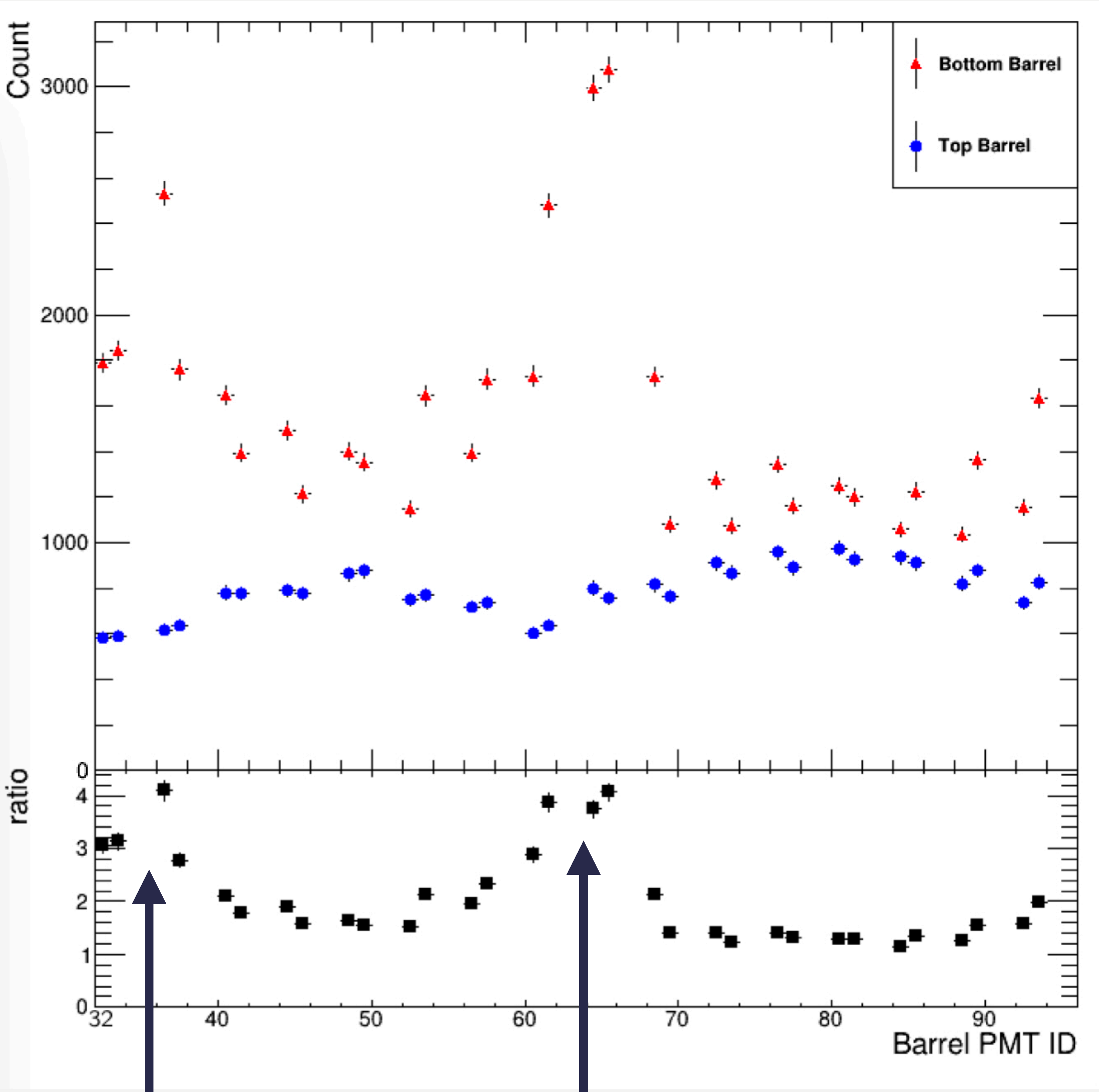




PMT ID - Diffusor
Directed photons

- Expect two peaks in the count of PMT hit
- Should still be a ratio of one if the diffusor is pointed perpendicular in the tank.
- Confirmation that the diffuser is not pointing correctly





Edge

Middle

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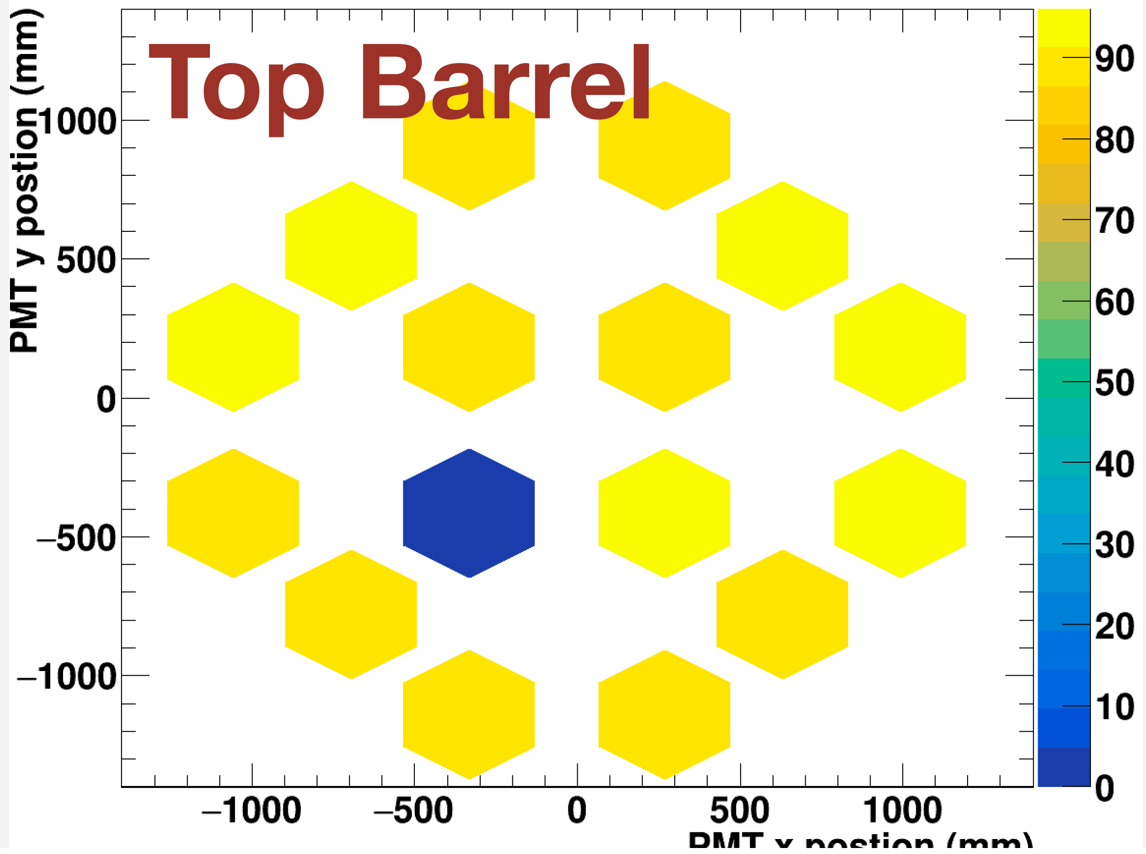
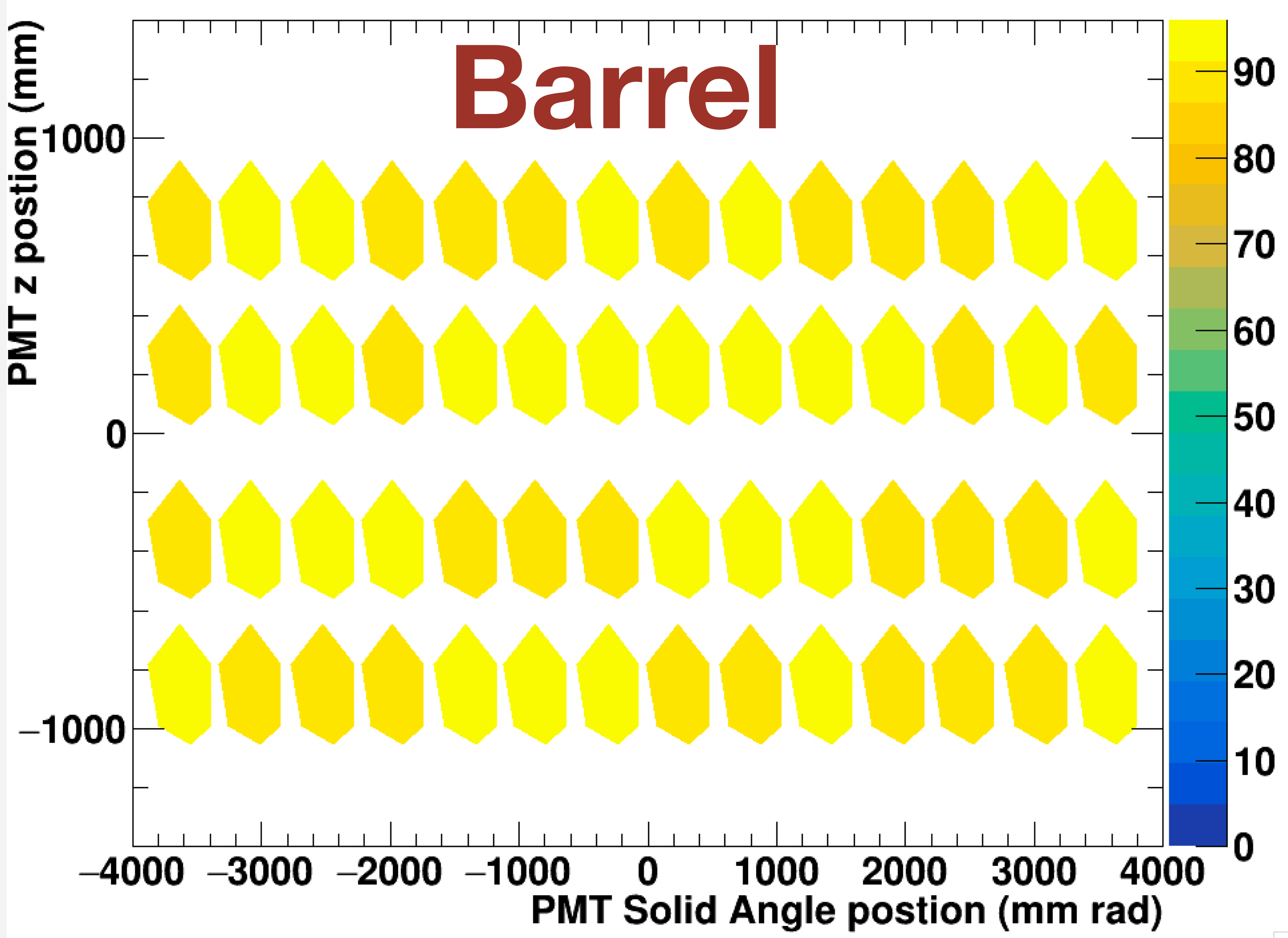
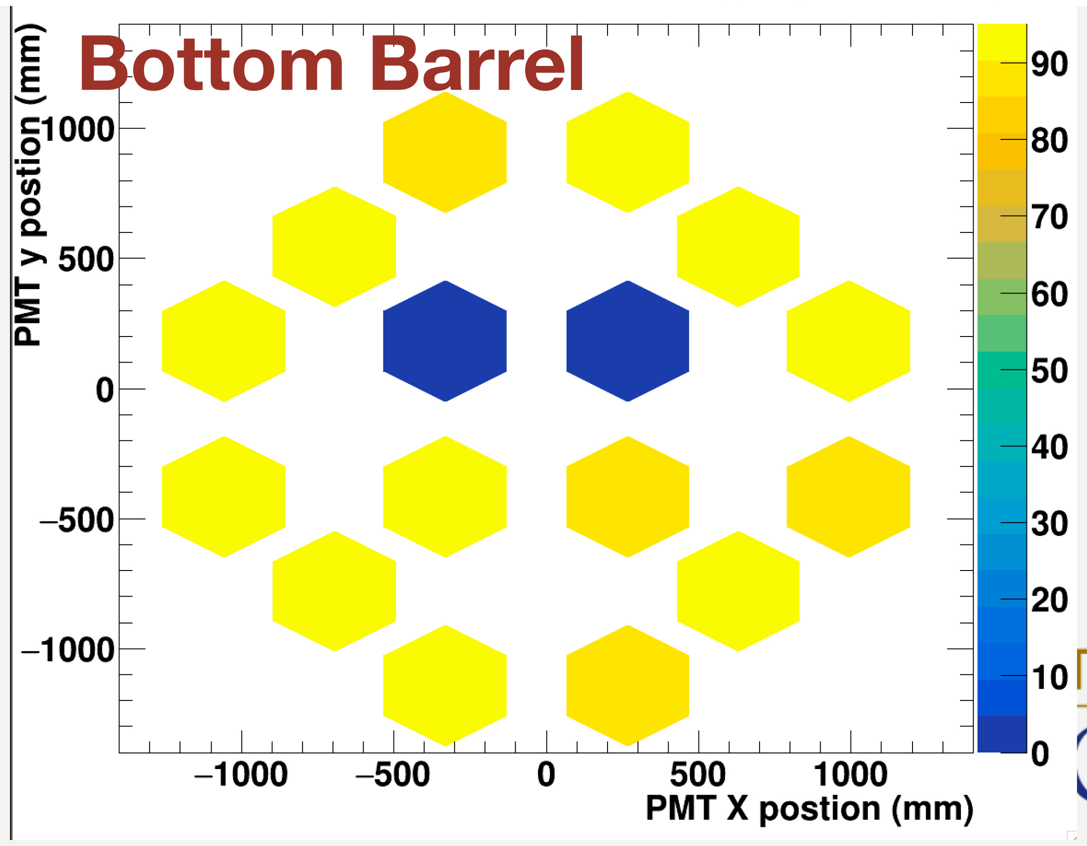
Working towards an event display

Being steps

- Started to use 2d hist to plot charge/hit for the pmt position
- Top and bottom easy to achieve
- The barrel was more difficult and required thought in the end using the solid angle to combine the x and y while stopping overlap
- To make the cells clear using a TPoly to make each bin a hexagon which only that PMT can fill with hits (A lot harder then it looked)
- Lets turn it into a full display …..



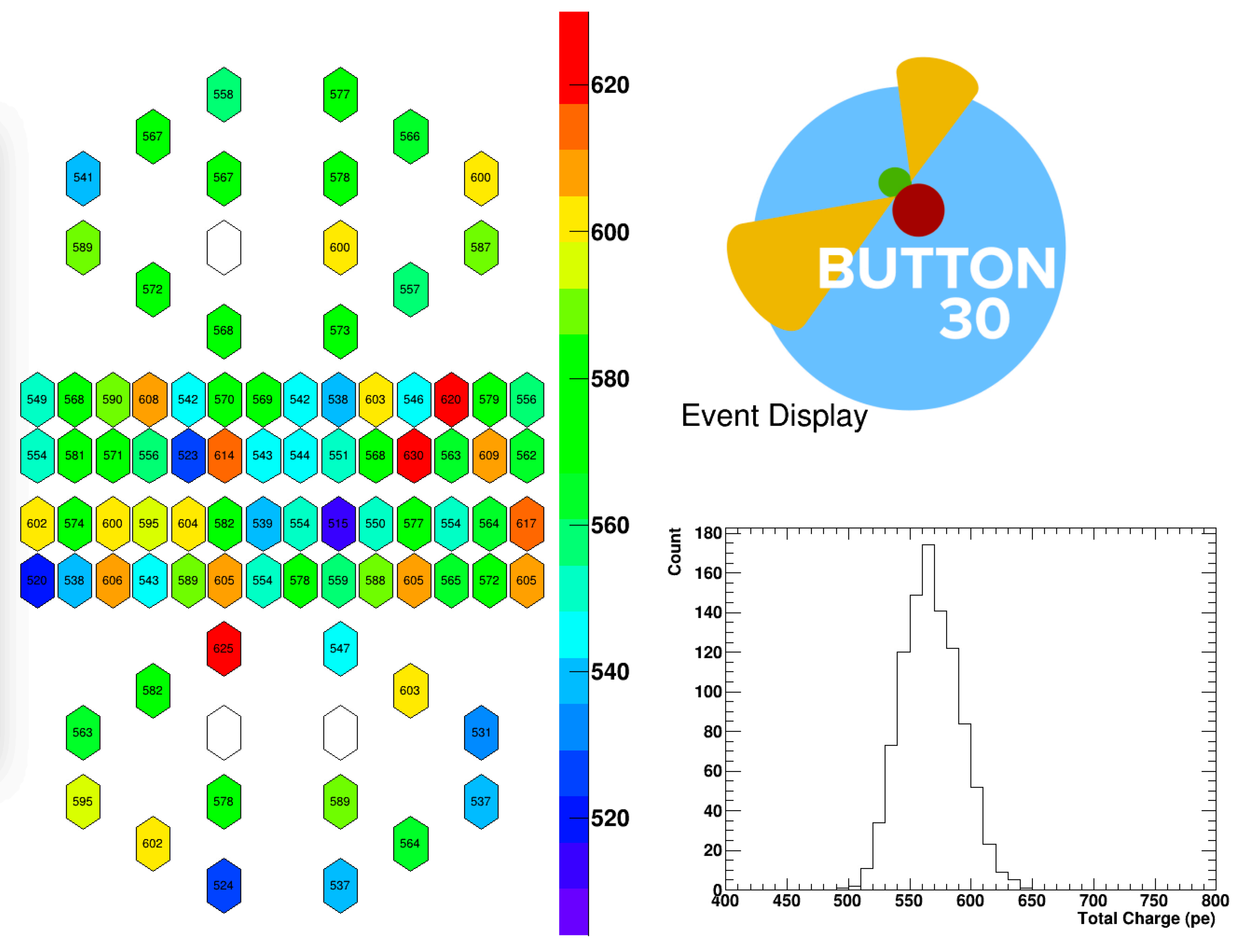




A working event Display

With Logo

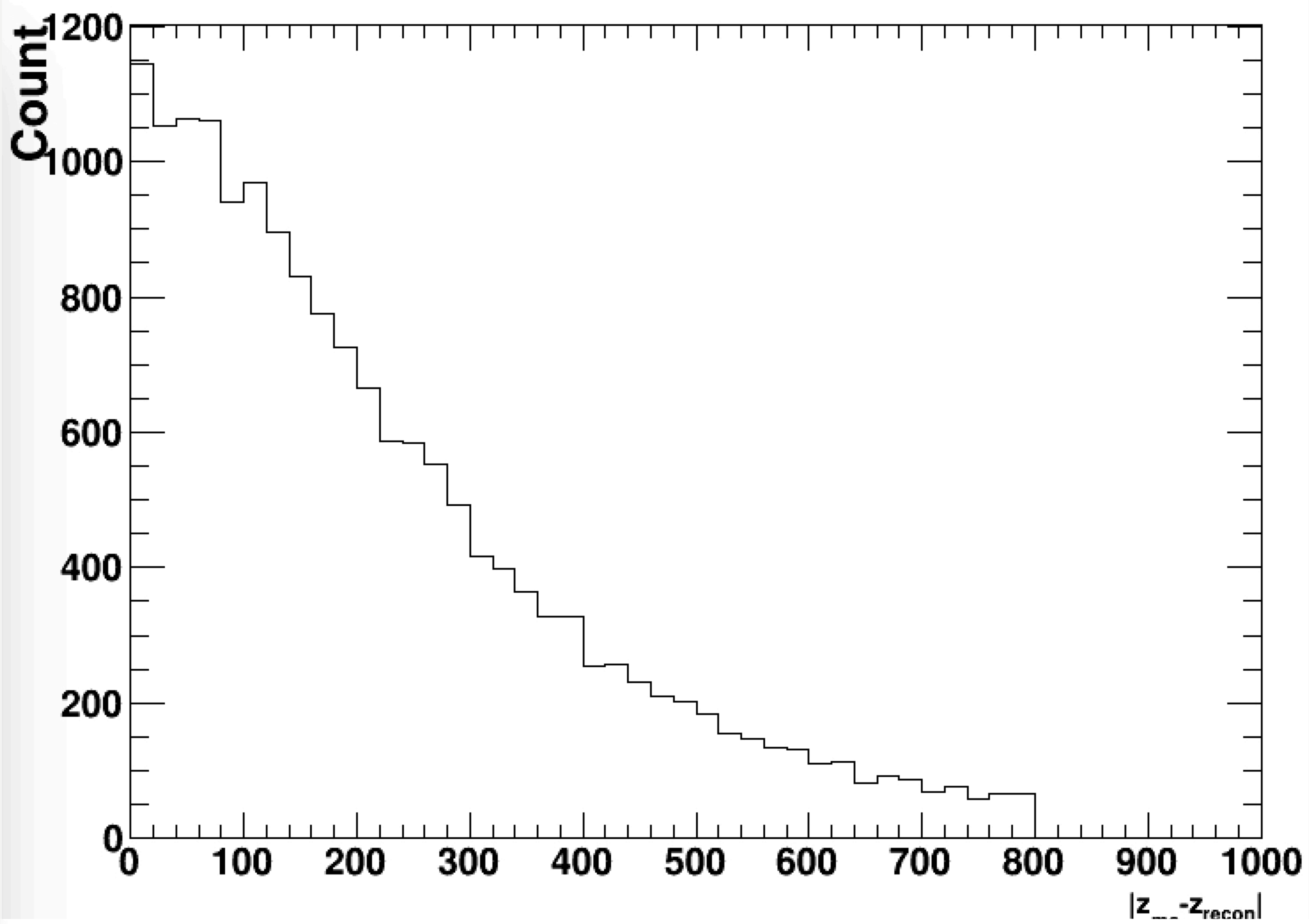
- Combined the 3 TPolys into a single canvas (scaling)
    - Had to find a way to make them all use the same colour scheme
- An additional 3 tpolys use an array of the pmts to produce a black outline therefore allowing a black boarder
- Can choices between charge or hit
- Even added a logo in the corner (there was a free space on the canvas) can be turned on off (takes ages to load)

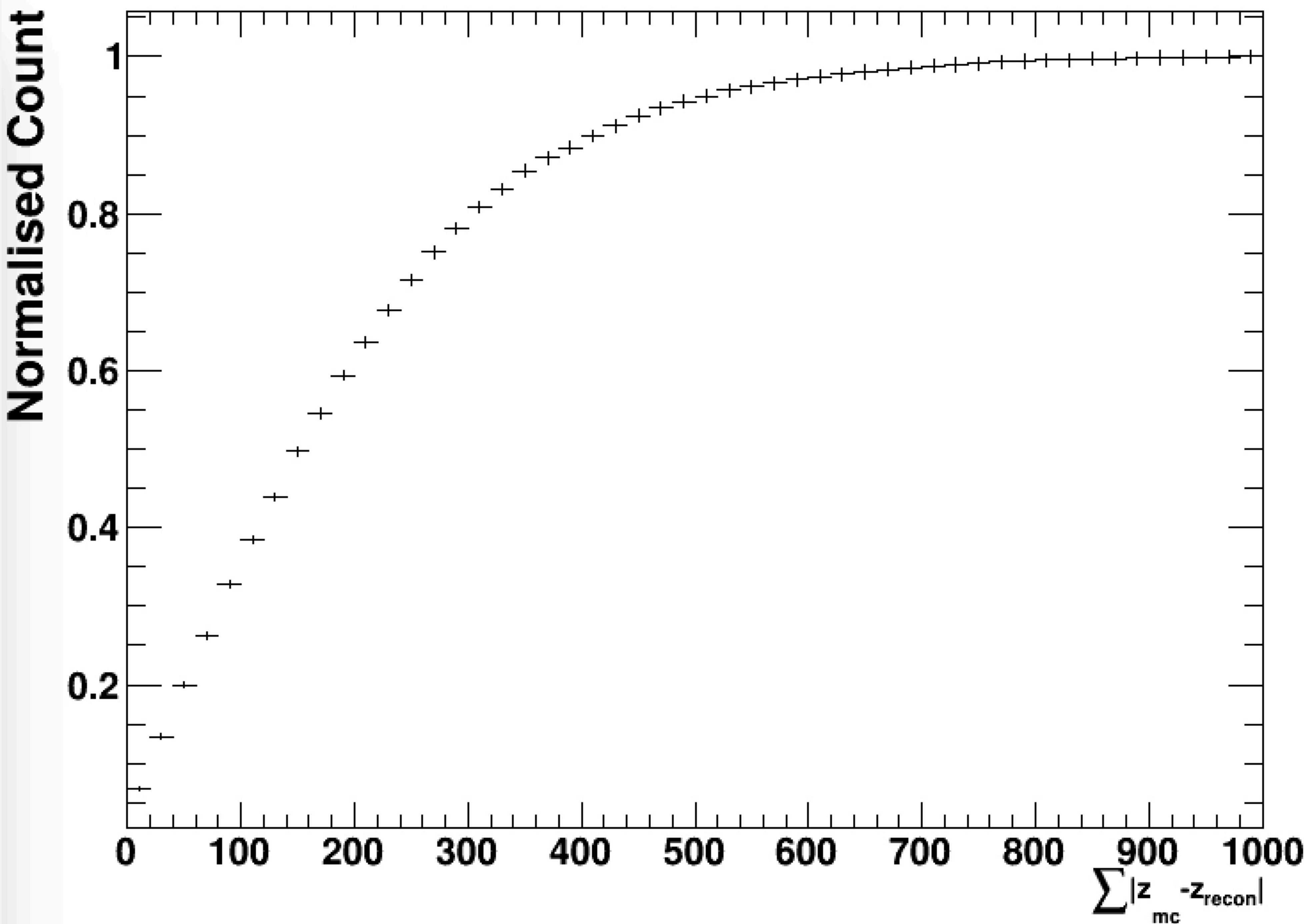


Disco Ball (Diffuser ball)

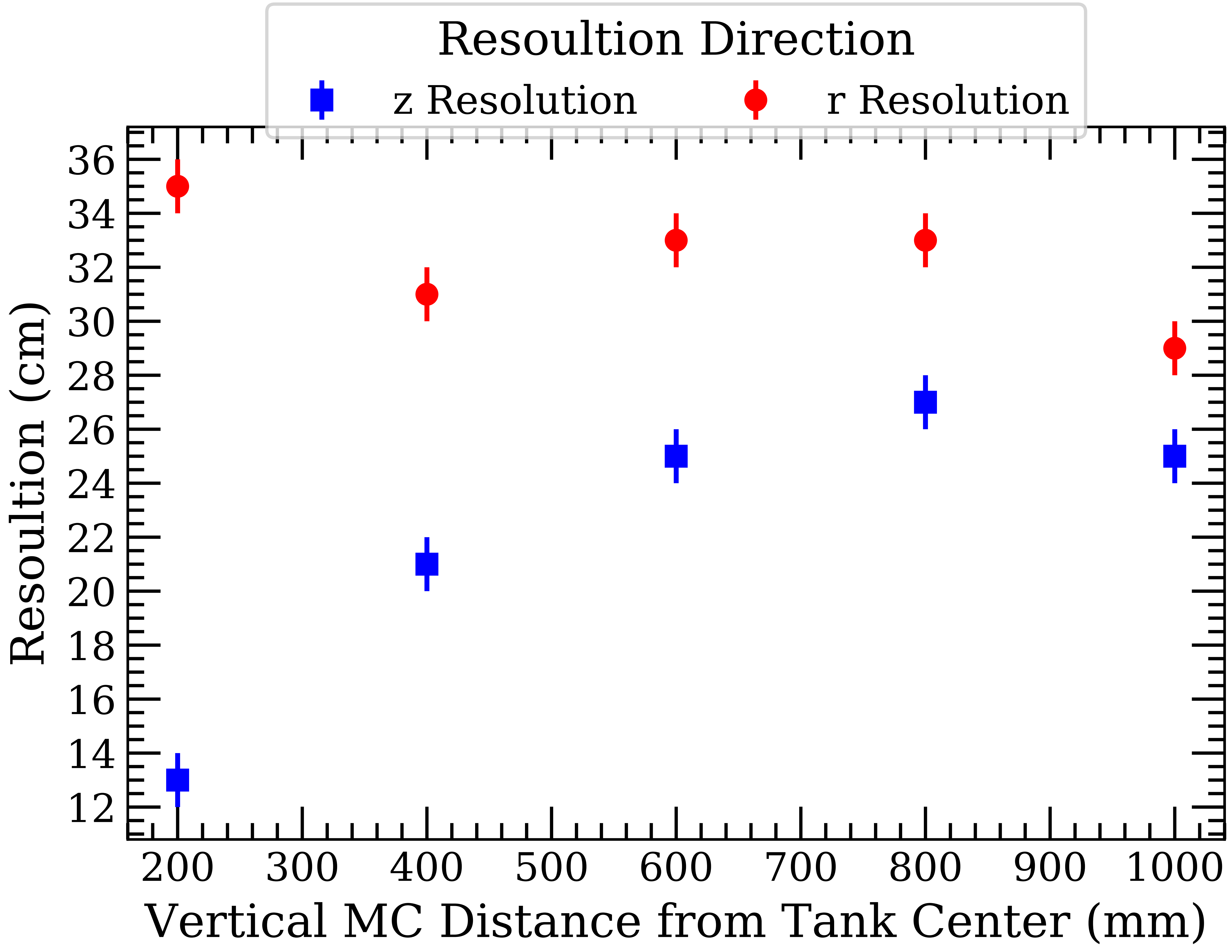
Diffuser ball

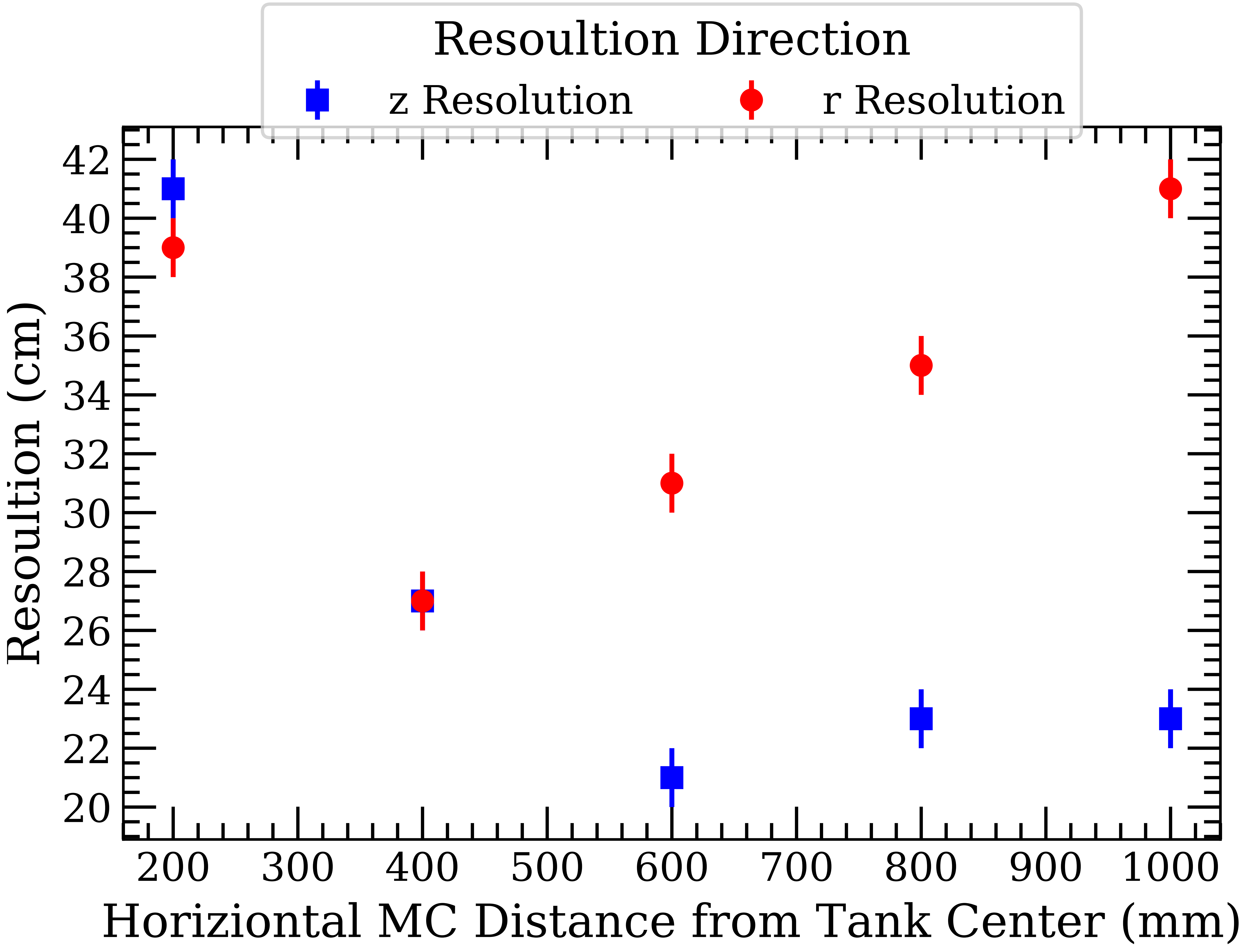
- Using the photobomb (uniform) to represent a Diffusor ball. (This ignore that the real thing wouldn't be uniform)
- Using the same method I used for the vertex resolution
  - Find the difference between Monte Carlo and reconstructed $|z_{mc} - z_{recon}|$ < 68%
  - Require the goodness of position >0.1 (truncated χ^2)
- 50k * 10k optical photon from diffuser ball changing in vertical of horizontal position





Vertex Positioning





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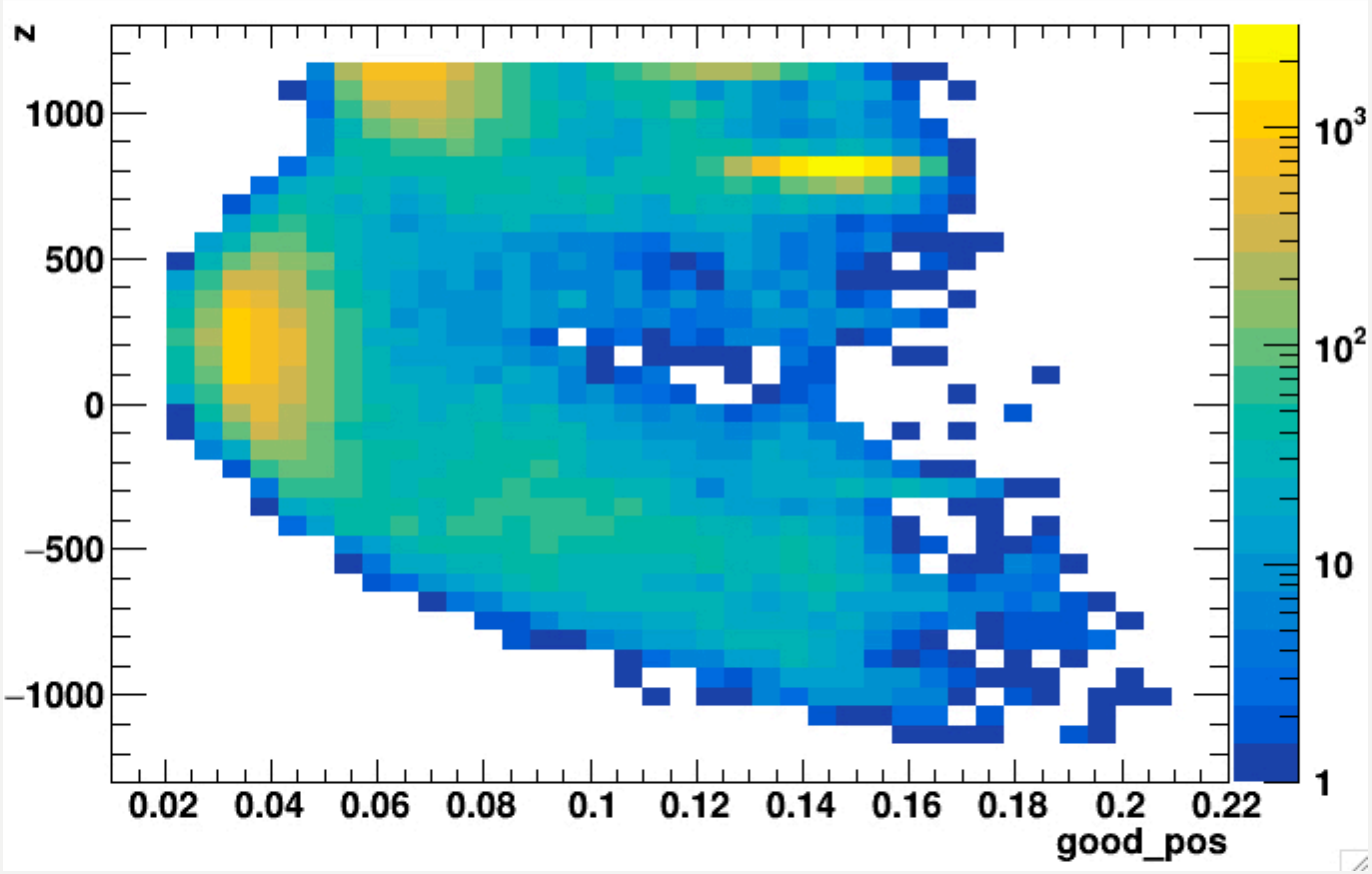
Goodness and z reconstruction

Z vertex



Time Residual

Time separation with Photons

- Time residual between Cherenkov and Scintillated photons.

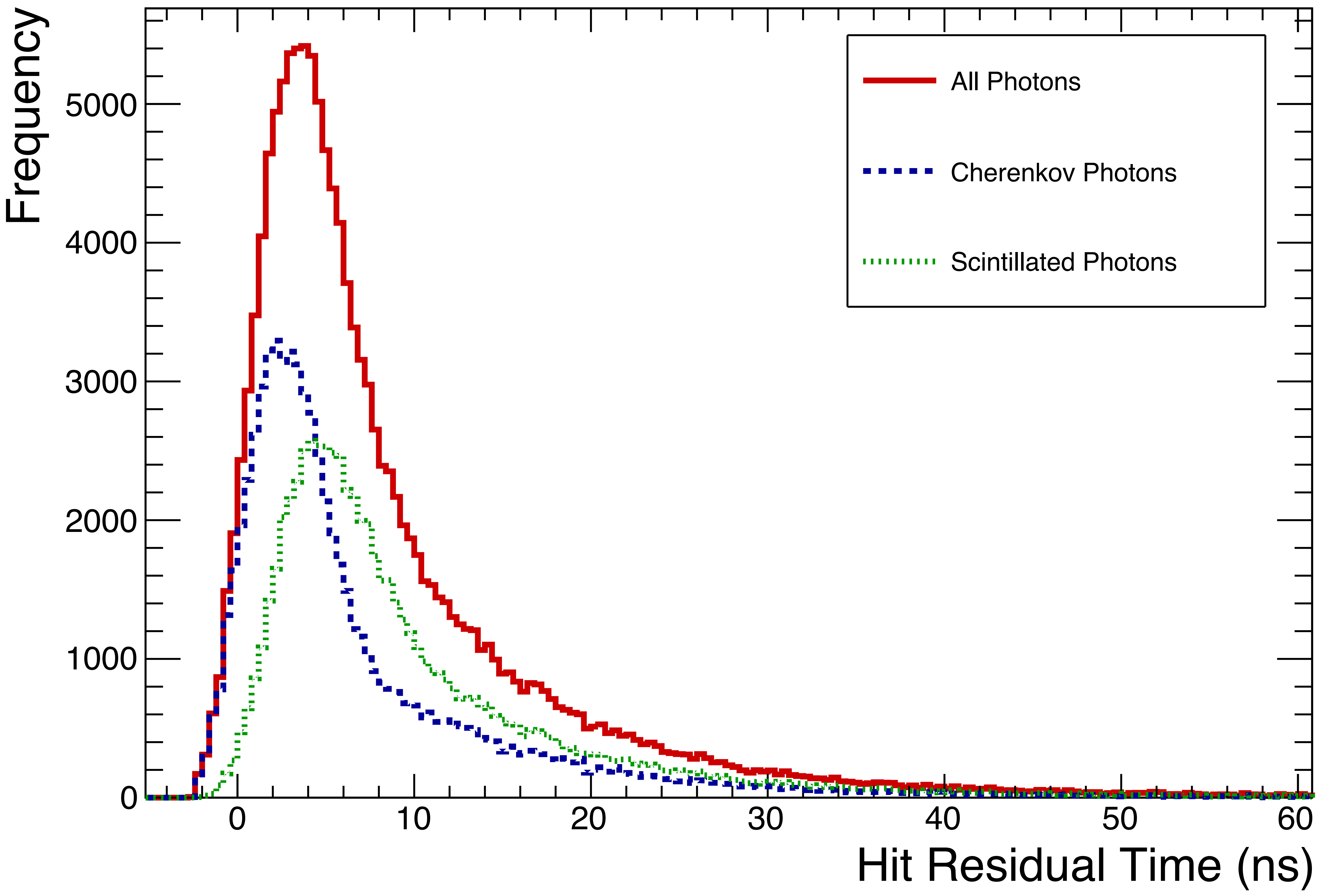
- Speed of light in WbLS c_{WbLS} = 20.5 cm/ns

1. $t_D = \dfrac{|V_{pmt} - V_{event}|}{c_{WbLS}}$

2. $t_{pmt} = t_{hit} + t_{trigger}$

3. $t_{Res} = t_{pmt} - t_D$

- Time separation = (2.377±0.001) ns



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